Space Physics Strategy–Implementation Study

Volume 2: Program Plan

Report of Workshop 2
June 18-21, 1990
Bethesda, Maryland

A Report
to the
Space Physics Subcommittee
of the
Space Science and Applications
Advisory Committee

April 1991

Dedication

This report is dedicated to the memory of Stanley Dean Shawhan, the first Director of the NASA/OSSA Space Physics Division.

On the last morning of his life, June 21, 1990, Stan presided over a plenary session of this Strategy-Implementation Workshop, in which the consensus view of the goals and programs of the Division for the years 1995–2015 was reviewed by the participants. The consensus was hard won, and it was newly won. A straw vote the previous afternoon had revealed a workshop still struggling to balance equitably the many conflicting and valid needs of the four disciplines comprising space physics: cosmic and heliospheric physics; ionospheric, thermospheric, and mesospheric physics; magnetospheric physics; and solar physics.

Then Stan Shawhan went to work. Wednesday evening, June 20, 1991, following the straw vote, was devoted to a meeting of the workshop steering group: the chairs and co-chairs of the four discipline panels, the Mission Integration and Divisional Science Panel, and Stan Shawhan. In the absence of a clear workshop vote, the steering group had to choose between four very different divisional plans that had been designed by "scenario working groups" and then evaluated by the discipline panels. The steering group evolved two ground rules whose repeated application finally enabled the planning process to converge. The plan had to be *livable:* the major scientific goals of each discipline must be attended to. And the first years of the plan had to be manifestly *doable,* technically, financially, and politically. Each scenario was modified where it failed to meet a disciplinary major goal; each was modified where it appeared not to be doable in the short run. The evolving scenarios began to look more and more alike. Ultimately, the steering group declared them fundamentally indistinguishable, and refined them into one plan (with and without a Space Exploration Initiative [SEI] augmentation) that was confirmed by the discipline panels and the workshop as a whole the next morning.

Stan Shawhan's understanding of the basic science under his Division's purview, his ability to convey to impatient scientists the practical problems faced by his Division, his personal warmth and tolerance—all played a major role in creating a consensus that had seemed distant only a few hours earlier, a consensus that other NASA groups had tried and failed to reach.

It seemed to all present Thursday morning that Stan Shawhan had achieved more than a long-range research plan. He had molded the people and programs represented by NASA's newest Division into a research community. In a post-workshop session that afternoon, Stan led a discussion of where the community would go from here. Some missions would need early reassessment. A strong rationale both for establishing the new intermediate class of missions and for enhancing the Explorer program would need to be developed. The research base (MO&DA, SR&T, ATD) would need to be reexamined and science balance across the field centers addressed. Yet he spoke confidently of these and the other issues seemingly certain that, having come this far, the Division and the community could readily solve the many problems still before it. The legacy Stan left is both the plan and the challenge of bringing it to reality.

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1.0 Introduction

In June, 1989, the Space Science and Applications Advisory Committee (SSAAC) authorized its Space Physics Subcommittee (SPS) to prepare a plan specifying the future missions, launch sequence, and encompassing themes of the Space Physics Division. The plan, now complete, is the product of a year-long study comprising two week-long workshops—in January and June 1990—assisted by pre-workshop, inter-workshop, and post-workshop preparation and assessment activities. The workshops engaged about seventy participants, drawn equally from the Division's four science disciplines: cosmic and heliospheric physics, solar physics, magnetospheric physics, and ionosphere-thermosphere-mesospheric physics. An earlier report records the outcome of the first workshop; this is the report of the final workshop.

The future-missions plan that resulted from the SPS study is a highly refined product. It defines a suite of outstanding missions. It introduces new concepts while building on applicable strategy documents.* It articulates themes that unify and aim the Division's program. It would change the mission-size categories and the balance between big and small missions. It exploits the capability of space physicists to build needed instruments. It satisfies prescribed cost constraints. It meets Space Exploration Initiative (SEI) responsibilities and capitalizes on SEI opportunities. It invites international collaboration. It balances flight access across the Division's science disciplines, and—very importantly—it achieves community consensus.

Such refinement reflects the study that made it. To appraise the value the study added to the product, we outline its key programmatic elements. The main elements were the workshops, whose structures contributed effectively to the study's success. The basic structure was a set of six panels: one for each science discipline, a Theory Panel, and the Mission Integration and Divisional Science (MIDS) Panel, responsible for managing the interactions between discipline panels and integrating their outputs into a divisional plan. This basic structure is shown in Figure 1-1. The MIDS Panel had balanced discipline representation. Discipline panels brought to Workshop 1 mission scenarios and programmatic themes already well developed through pre-workshop meetings in public forums. Between panel and plenary sessions, discipline panels evolved their scenarios further in light of other scenarios and with guidance from MIDS and other panels. Thus, the discipline panels produced four scenarios, elaborated and polished in panel sessions, probed and critiqued in plenary sessions. The Theory Panel would give theorists more say in managing the Division's theory and data analysis programs and in designing missions. MIDS identified a needed category of mission size; it combined discipline scenarios in a mock-up, proof-of-concept divisional scenario; and it melded discipline programmatic themes into two broad divisional themes. All the effort notwithstanding, Workshop 1 delivered a product that was, as planned, only partially refined. Inter-workshop activities processed it further.

Inter-workshop business engaged designers in assessing technical and cost implications of Workshop 1 priority missions. Then the Workshop Committee—Shawhan, MIDS, and panel chairs and co-chairs—used Workshop 1 missions to assemble test scenarios that emphasized three mixes of mission sizes: three flagship missions with a few smaller missions, one flagship mission with more smaller missions, no flagship missions but many smaller missions. In official NASA parlance, flagship missions are major missions (around $1B or more); smaller missions are moderate missions (around $500 M to $1 B) and a new—not official—size category that this report calls "intermediate" (around $200 M). The scenarios excluded Explorer-class missions (around $100 M) because present rules of competitive selection preclude labeling them programmatically and, thus, identifying them explicitly in mission scenarios. The three size mixes reflect different modes of doing business: a few big missions at one extreme and many small missions at the other. The advantages of smaller missions are hope of more flexibility, more flights, and less programmatic risk. The three assortments

* *The OSSA 1991 Strategic Plan, Space Science in the 21st Century—Solar and Space Physics (NAS, 1988), An Implementation Plan for Priorities in Solar System Space Physics (NAS, 1985), Strategy for Explorer Program for Solar and Space Physics (NAS, 1983)*

of mission sizes in the test scenarios let Workshop 2 evaluate, for the given constraints, the optimum mix for space physics.

The inter-workshop test scenarios were input material for Workshop 2 scenario panels—one panel per size mix. Scenario panels—regroupings of discipline panel members—tailored their input scenarios to fit cost constraints and to insure adequate flight access for each discipline. The discipline panels reconvened at preset times to coordinate their reactions to the scenarios as they evolved. A fourth panel, on SEI, developed scenario modifications to meet SEI needs and identified scenario enhancements to exploit SEI opportunities. The scenario panels of Workshop 2 are also shown in Figure 1-1.

The final element in the process is closure—the means to winnow scenario options down to one. The Dedication to this report describes how it happened at Workshop 2. The final products of each scenario panel evolved in open forum by progressive mutations (addition or subtraction of missions, one at a time) to avoid extinction under the dual threats of being "unlivable" (a major discipline goal unmet) or "undoable" (too costly, too hard, or unsalable). The result was rapid, convergent evolution to a common, livable, doable, consensus scenario.

This report describes the output of the study: the final scenario, the programmatic themes it addresses, the changes needed to implement it, and its missions individually in depth.

Many people worked hard to make the study succeed. Special thanks go to Nat Cohen of Science Applications International Corporation (SAIC) who orchestrated Workshop 2 and the inter-workshop and post-workshop activities in a masterly fashion and to Ken Fox of SAIC who chaired Workshop 1. SAIC staff were tireless in their support of workshop efforts; their performance materially increased workshop productivity. The science staff of the Space Physics Division—Tom Armstrong, Dave Bohlin, Dave Evans, Vernon Jones, Ken Lang, Jim Ling, Mary Mellott, and Bill Wagner—were always ready with information and assistance to keep things going. Goddard Space Flight Center, Jet Propulsion Laboratory, Marshall Space Flight Center, and SAIC provided essential technical and cost assessments to the study. The assessment project was orchestrated with remarkable speed by Bob Farquhar of Goddard and managed by Bob Cooper of SAIC. The seventy-some workshop participants worked from 8 AM to 10 PM for five days twice on behalf of the study. The panel chairs and co-chairs also wrote reports, organized pre-workshop meetings, and attended Workshop Committee meetings. The effort was prodigious and the achievement reflects it. Panel chairs, co-chairs, and members are cited on a later page of this report. Then there was Stan Shawhan. His intellectual presence and energy dominated all phases of the study up to the final minute of the final workshop. Now his spirit will guide its implementation.

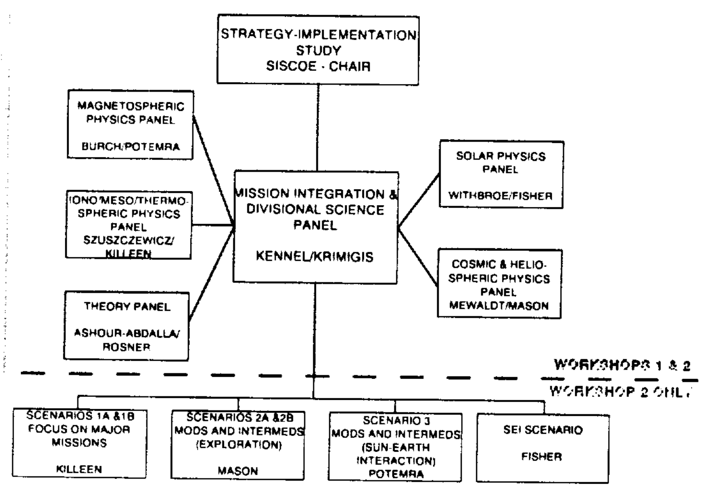


Figure 1-1. Strategy-Implementation Study structure

2.0 MIDS Panel Overview

2.1 Role of the MIDS Panel

The members of the Mission Integration and Divisional Science (MIDS) Panel were drawn from each of the four major disciplines comprising space physics, chosen in part for breadth and tolerance of viewpoint. As the name implies, the function of the MIDS panel differed from all the others. It did not originate new disciplinary goals or propose new missions. Its job was to guide the Workshop into fashioning a unified divisional plan. It defined *themes* that identified the general scientific goals of space physics as well as the specific thrusts that would characterize the space physics research of the next twenty years. Perceiving, communicating, and discussing these themes, the workshop participants achieved a degree of harmony. Secondly, teams of MIDS panel members were assigned to attend meetings of each discipline and scenario panel. They communicated the flavor of the panel discussions to the MIDS panel as a whole, and, in return, conveyed to the panels the divisional perspective of the MIDS panel as it evolved. Thus, the plan for the Space Physics Division resulted from extensive iteration and feedback.

2.2 Themes Characterizing Space Physics

The following overarching theme defines our subject:

> *Space physics is the study of the heliosphere, that is, of the Sun, solar wind, and cosmic rays, and their interactions with the upper atmospheres, ionospheres, and magnetospheres of the planets and comets, and with the interstellar medium, as one system.*

Space physicists have composed similar disciplinary definition statements over the years since 1958, when the subject came into being with the discovery of the Earth's radiation belts by Explorer I. That these statements have changed slowly with time reflects the enduring and fundamental nature of our scientific concerns. What is new about the most modern version of the disciplinary theme above is the phrase "*as* one *system*": in the next twenty years we will begin to study the entire heliosphere as a unified entity for the first time.

Research in space physics requires information and techniques from many scientific disciplines, but one stands out:

> *Space physics is, to a great extent, the study of naturally occurring plasmas. These are of many different types, including the partially ionized relatively cool plasmas of planetary ionospheres, the million degree plasmas found in the solar corona, the solar wind, and planetary magnetospheres, and the highly relativistic galactic cosmic ray plasma. They not only have very different physical scales, but each has within it phenomena occurring on a wide range of scales. The challenge for space plasma research is to relate large- and small-scale phenomena.*

Understanding space plasmas requires concepts drawn from the frontier of modern theoretical research on the nonlinear interactions between large- and small-scale phenomena.

The significance of solar and galactic cosmic ray research, in particular, extends beyond space physics:

> *Studies of the origin, composition, acceleration, and transport of energetic particles are an important component of heliospheric research that makes direct contributions to stellar and galactic astrophysics.*

Finally, the human exploration of space and the study of the terrestrial environment are enduring parts of NASA's mandate that will receive renewed emphasis in the coming years:

> *On the directly practical side, the knowledge acquired by space physics research is critically important to understanding the effects of energetic particles and solar variability upon the Earth's environment and the human exploration of space.*

2.3 Themes Characterizing the Next Twenty Years

"Overarching themes" like those above are intended to describe what a discipline does and who is in it. Now we turn to themes that can convey the flavor of the space physics research we foresee in the next twenty years. In short, we emphasize the particular emphases of the new space physics research NASA will carry out.

We will continue our ***exploration*** of the Earth's and Sun's space environment, we will achieve a new kind of scientific ***understanding***, and we will create a new ***approach*** to the planning and management of space physics research.

2.3.1 Exploration

We will go to the frontiers of the solar system: the Sun and the interstellar medium

In short, space physics will come to share the leadership in the exploration of the solar system with the planetary sciences. *The next frontiers of solar system exploration are the very limits of the heliosphere—the Sun and the interstellar medium. These are space physics missions.* A mission to the Sun, the Solar Probe, is the centerpiece of the first decade of the Division's plan, and we expect to get started on an Interstellar Probe by the end of the second decade.

Once we have explored the Sun and interstellar medium *in situ*, we will be in a position to start the integrated study of the *entire* heliosphere as one interacting system. This integrated study has been under way for parts of the heliospheric system for some time.

2.3.2 Understanding

To understand the interacting systems comprising the heliosphere, we must relate global behavior to small-scale physical processes. This requires us to integrate the panoramic three-dimensional view obtained by global images with multi-point in-situ *measurements in every area of space physics.*

Our exploration of the solar system started near the Earth and progressed outward. We have already learned much about the Earth's upper atmosphere, ionosphere, and magnetosphere, and about the solar wind in the Earth's neighborhood. We have come to understand that these are parts of a grand interacting system—the heliosphere—that derives its energy from the Sun. We have begun to appreciate that the heliosphere is basically cellular in structure, comprised of distinct but interacting regions—the mesosphere, the thermosphere, the ionosphere, the magnetosphere, the solar wind, and so on. The "cells" interact across relatively thin layers that separate them. Today's challenge is to perceive the extent and behavior of each cell, and to understand the small-scale processes regulating their interactions, so as to progress toward comprehensive understanding of the heliosphere as one interacting system.

Even within the cells the important processes can occur on a daunting variety of space and time scales. The need to understand nonlinearly interacting global and microscopic processes on a hierarchy of scales is one of the central problems of late twentieth-century science. Space physics measurements have already partly revealed the hierarchy of scales, and the space physics community has had to evolve a research strategy that copes with two inherent limitations of experimental technique: that *in-situ* measurements characterize microprocesses, but only at one point in space at a time, while the global view provided by remote sensing often lacks the resolution needed to detect and understand the relationship to the important microprocesses that affect macrostructure. The research programs outlined in this document reflect a creative and thoroughly modern approach to these fundamental issues.

To carry out this new approach to our research, we must also approach the management and planning of our research in a new way.

2.3.3 Approach

The evolution of space physics will force a more integrated approach to the planning and management of its research.

None of us can define with complete assurance what the words "integrated approach" actually mean in this context, but it is already clear that a new mode of thinking, working, and organizing is needed, one that promotes the integration of information on many different physical scales that we hope to achieve in our research.

Integration, to us, means in part greatly increased integration of distributed information into knowledge using electronic data exchange. It means the integration of theory and modeling into project conception and design as well as data analysis. It means the systematic integration of single spacecraft into spacecraft systems, in which the spacecraft itself is a subordinate part of the project. In short, we will have to reconceptualize what the word "mission" means. It means a change in the way we think about research planning and administration:

We urge that NASA take a "knowledge acquisition systems" approach to the conception, design, and management of research in space physics.

Finally, the words "more integrated approach" mean that more attention must be paid to the appropriate distribution of research projects by size. NASA has long prided itself on the disciplinary balance of its overall space science program, and with good reason. However, one can also ask: "What is the appropriate balance between scales of research effort?"

2.4 A New Mission Class

The results of this planning workshop suggest that the present distribution of spacecraft projects by size may not be scientifically appropriate to space physics research in the future. The present OSSA plan has categories for moderate and major missions, costing between 0.5–1 and 1 and 2 billion 1990 dollars, respectively. Present decision rules specify that one major new start will be submitted to Congress each year; barring that, a moderate mission will be submitted. However,

Space physics research will require a greatly expanded program of intermediate-scale spacecraft missions in the next twenty years.

The intermediate missions discussed in this document will cost on the order of 200 million dollars and many will cost substantially less. A mission may involve one or more spacecraft. After a detailed examination of the scientific and programmatic needs of each of the four subdisciplines comprising space physics in several different scenarios, our workshop has concluded that an adequate intermediate mission line could be as important to the progress of space physics as the current major or moderate mission lines:

In the aggregate, intermediate missions comprise a critical element of the research program of each of the disciplines in the Space Physics Division.

The mere fact that a project is relatively small does not mean that its scientific benefits will also be small: the importance of scientific knowledge cannot always be measured by the cost of acquiring it.

In the past, projects similar to, but typically somewhat smaller than, those we envision for the Intermediate class have been funded through the Explorer line item. Despite its recent augmentation, the Explorer budget is far from meeting the need in space physics, let alone astrophysics. This has led us to conclude that:

Present OSSA resources and procedures do not meet the projected need for intermediate projects in the Space Physics Division.

In view of the above,

We recommend that the OSSA strategic plan explicitly include an intermediate mission category.

The present plan, which was designed to create scientific opportunity while attending to the backlog of delayed missions following the *Challenger* disaster, may well need modification for the period after 1994. We suggest that there is a missing element in the spectrum of mission sizes in present planning rules: intermediate missions. The simple act of establishing an intermediate mission category could stimulate technological advances to reduce the cost and increase the flexibility of small and intermediate spacecraft projects.

We understand the general reluctance to increase funding for line items—one reason why the Explorer line has failed to keep up with inflation and the scientific need for it. However, we are confident that the intermediate projects proposed here can win Congressional approval on their merits, once the case for the intermediate category has been made and is understood.

3.0 The Post-ISTP Space Physics Mission Scenario

The Space Physics Division (SPD) mission plan covers the period 1995–2010 and was constructed through the grass-roots involvement of the science community via the conduct of open workshops in the four broad discipline areas of solar, cosmic and heliospheric, magnetospheric, and ionospheric-thermospheric-mesospheric physics. The products resulting from the workshops, together with theory, were integrated into an overall SPD program plan that has combined the highest-priority elements from each area into a timeline that achieves discipline balance, a mix of major, moderate, and intermediate missions, and a roughly constant funding profile of about \$600M per year. Major missions (> \$1B) include the Solar Probe (currently in the OSSA Strategic Plan) and the Ionosphere-Thermosphere-Mesosphere Coupler; moderate missions (~ \$500M) are the Mercury Orbiter, High Energy Solar Physics, and Grand Tour Cluster; and intermediate missions (≤ \$200M) include Auroral Cluster, Ultra Heavy Cosmic Ray (UHCR), Inner Magnetosphere Imager, Solar Probe Coronal Companion, and Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED). The decision rules and boundary conditions adopted for the construction of the plan will be described and possible options and fall-back positions will be discussed. The latter are particularly pertinent in view of the uncertainty at present surrounding the overall NASA budget.

3.1 The Consensus Program

In the process of designing this program the

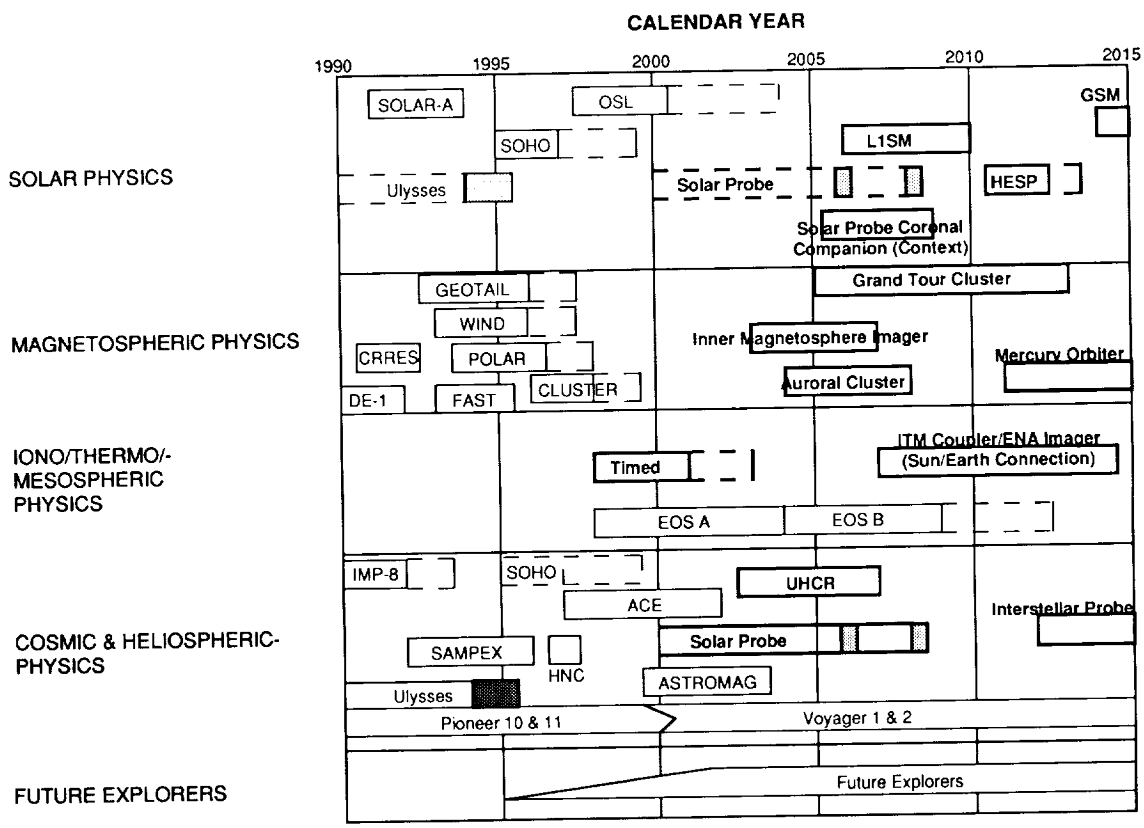


Figure 3-1. Timeline of the consensus scenario without SEI for the period 1990 to 2015

study group, in addition to assuring that the program's three themes for space physics were satisfied (i.e., exploring the solar atmosphere and the inner heliosphere, understanding the Sun and its effects upon the Earth's magnetosphere and upper atmosphere; exploring to the frontiers of the heliosphere and interstellar space), evolved the following guidelines: (1) To advance understanding in each of the domains of space physics (i.e., solar physics, magnetospheric physics, ionospheric-thermospheric-mesospheric physics, and cosmic and heliospheric physics) and the chain of interaction among them, a broad scientific attack is necessary. This requires a major thrust in each of the separate disciplines identified above. (2) There is a need for major missions to perform studies on a global scale, moderate missions for more specific problems, and intermediate missions for sharply focused, constrained studies that attack specific scientific problems. (3) It is essential to establish the level of flight activity necessary to address significant scientific issues. (4) The plan must be accommodated within a realistic budget that can remain stable over a period of several years and allow the planning and analysis essential to a successful research program.

Table 3-1 lists the missions so chosen, and includes a brief description of scientific and measurement objectives for each. This consensus program contains a mix of major, moderate, and intermediate missions, strives for balance among space physics disciplines and takes into account the flight activity in each, as planned at present from 1990 onwards. Opportunities for small missions have not been specifically addressed but are expected to be satisfied through the Explorer program administered at the present time by the Astrophysics Division. The program is divided into two scenarios. The baseline scenario assumes no Space Exploration Initiative (SEI); the second scenario assumes that the SEI program supports related space physics missions. In addition an SEI lunar base scenario was developed separately.

Figure 3-1 shows a timeline in schematic form of the consensus scenario without SEI over the period indicated for each of the four major discipline areas. To provide appropriate context, approved missions expected to be operating from 1990 on are included. Note that like Ulysses and Solar Polar, many missions contribute to more than one area, but for clarity only those two are shown in more than one panel.

Starting at the top panel we observe that the solar physics discipline expects to have substantial data through the year 2000 via combination of the ISTP/SOHO program and the implementation of OSL. The Solar Probe is shown in dashed-line from the year 2000 onward because it is the principal mission for cosmic and heliospheric physics, but it is of equal importance to solar physics as well. An essential part of the Solar Probe program is the Solar Probe Coronal Companion which is intended to provide the context during which the approach of the probe spacecraft will take place. The exact relationship between these two projects is to be decided during the implementation plan for the overall program. The L1 Solar Monitor (L1SM) is intended to provide information on solar variability and high energy astrophysical processes of solar flares and active regions with a single spacecraft located at L1. The High Energy Solar Physics (HESP) mission, designed to provide high resolution imaging of hard X rays and gamma rays during the solar maximum period immediately following 2010 is shown after that time. If HESP can be scaled down to an intermediate-class mission, it should be considered for the earlier solar maximum period centered on 2002, taking advantage of simultaneous SOHO and OSL observations. Finally, a Global Solar Mission, including spacecraft in the ecliptic at 120° from Earth and one Solar Polar spacecraft, is shown at the end of the planning horizon.

The second panel shows flight activity in magnetospheric physics with the most significant early component being elements of the currently planned ISTP program, which includes Wind and POLAR from the U.S., Cluster and SOHO from Europe, and GEOTAIL from Japan. It is expected that the ISTP spacecraft will provide sufficient data to keep the community occupied through the end of the century, with additional focused studies to be performed utilizing the Explorer program (not shown here). Early in the next century the Inner Magnetosphere Imager (IMI) and Auroral Cluster missions are shown, both of which are intended to

SOLAR PHYSICS MISSIONS

SOLAR PROBE CORONAL COMPANION (CONTEXT) INTERMEDIATE MISSION	LARGE-SCALE TIME-VARYING STRUCTURE OF SOLAR CORONA FROM EARTH ORBIT AT THE TIME OF SOLAR PROBE ENCOUNTER.
L1SM MODERATE MISSION	SOLAR VARIABILITY AND HIGH ENERGY ASTROPHYSICAL PROCESSES OF SOLAR FLARES AND ACTIVE REGIONS WITH SINGLE GSM ECLIPTIC SPACECRAFT AT L1.
HIGH ENERGY SOLAR PHYSICS MODERATE MISSION	HIGH RESOLUTION IMAGING AND SPECTROSCOPY OF HARD X-RAYS, GAMMA RAYS, NEUTRONS TO STUDY PARTICLES IN FLARES AND CORONAL DISTURBANCES, ENERGY FLOWS; PLASMA PHYSICS OF NON-THERMAL SOLAR PARTICLES.
GLOBAL SOLAR MISSION (GSM) MAJOR MISSION	SOLAR PARAMETERS (E.G., FIELDS, DIFFERENTIAL ROTATION, SOLAR WIND, HELIOSEISMOLOGY, TEMPERATURE, CORONAL STREAMERS, AND MASS EJECTIONS) FROM 2 ECLIPTIC & 1 SOLAR POLAR (55 DEGREES) SPACECRAFT.

MAGNETOSPHERIC PHYSICS MISSIONS

AURORAL CLUSTER INTERMEDIATE MISSION	MICROPHYSICAL PROCESSES IN AURORAL PARTICLE ACCELERATION ON SCALE OF METERS TO HUNDREDS OF KILOMETERS.
INNER MAGNETOSPHERE IMAGER INTERMEDIATE MISSION	IMAGES OF GLOBAL RING CURRENT, PLASMASPHERE, AND INNER EDGES OF PLASMA SHEET.
GRAND TOUR CLUSTER MODERATE MISSION	TEMPORAL AND SPATIAL VARIATIONS IN CRITICAL MAGNETOSPHERIC REGIONS AND BOUNDARY LAYERS.
MERCURY DUAL ORBITER MODERATE MISSION	3-D MAP OF MAGNETOSPHERE AND PLASMA ENVIRONMENT; IMAGING OF MERCURY AT BETTER THAN 1 KM RESOLUTION; STUDY OF INNER HELIOSPHERE; AND MEASUREMENTS OF SOLAR X-RAYS, GAMMA RAYS, AND NEUTRONS

IONOSPHERIC/THERMOSPHERIC/ MESOSPHERIC PHYSICS MISSIONS

TIMED INTERMEDIATE MISSION	FIRST EXPLORATORY INVESTIGATION OF PLANETARY-SCALE ENERGETICS AND DYNAMICS IN THE COUPLED ITM SYSTEM FOCUSED ON CHEMICAL, ELECTRODYNAMIC, AND KINETIC FORCES AND ASSOCIATED RESPONSES IN THE PLASMA AND NEUTRAL PARTICLE DISTRIBUTIONS, INCLUDING CRITICAL MINOR CONSTITUENTS.
ITM COUPLER/ENA IMAGER MAJOR MISSION	ITM COUPLER: GLOBAL DISTRIBUTION OF ELECTRIC FIELDS, THERMOSPHERIC WIND, INTERMEDIATE PLASMA LAYERS, EUV/UV RADIATION, WIND SHEAR FORCES, ELECTRIC FIELDS IN INTERMEDIATE LAYERS; MESOSPHERE/LOWER THERMOSPHERE INTERFACE, FIELD LINE COUPLING IN UPPER F-REGION. ENA IMAGER: DISTRIBUTION AND DYNAMICS OF CHARGED PARTICLES AND EFFECTS OF STORMS AND SUBSTORMS IN MAGNETOSPHERE.

COSMIC AND HELIOSPHERIC PHYSICS MISSIONS

SOLAR PROBE MAJOR MISSION	IN SITU OBSERVATIONS OF THE SOURCE OF SOLAR WIND PLASMA AND EM FIELDS IN THE SOLAR ATMOSPHERE TO WITHIN 4 SOLAR RADII; DETAILED STUDY OF ENERGETIC PARTICLES, PROCESSES OF PARTICLE ACCELERATION, AND CORONAL STRUCTURE.
INTERSTELLAR PROBE MAJOR MISSION	EXPLORATION OF THE OUTER HELIOSPHERE, CROSSING BOTH SOLAR WIND TERMINATION SHOCK AND HELIOPAUSE, AND PENETRATION OF THE INTERSTELLAR MEDIUM. DETAILED STUDY OF INTERSTELLAR PLASMA, FIELDS, AND ENERGETIC PARTICLES.
ULTRA-HEAVY COSMIC RAYS INTERMEDIATE MISSION	ACCURATE MEASUREMENTS OF COSMIC RAY NUCLEI WITH 30<Z<96 INCLUDING CLOCKS IN THE ACTINIDE REGION; AGES OF HEAVIEST NUCLEI; OCCURRENCE OF TRANSURANIC NUCLEI; R- AND S- PROCESS NUCLEOSYNTHESIS; HISTORY OF PROPAGATION OF NUCLEI WITH 30<Z<82.

Table 3-1. Scientific and measurement objectives of missions in the consensus scenario without SEI

be in the intermediate-class category. Later on, the Grand Tour Cluster of spacecraft, intended to study various regions of the magnetosphere with orbit adjust capability, is shown and extends into the end of this planning horizon. Finally, a high-priority planetary mission, the Mercury Orbiter, is shown after the year 2010; it is intended that this mission be shared with the Solar System Exploration Division of NASA.

The third panel shows the ionosphere-thermosphere-mesosphere physics activity. It is evident from the figure that at the present time there is very little planned activity in this discipline area, which is newly incorporated into the Space Physics Division. The committee felt that an early start with an intermediate-class mission called TIMED would be of extreme value and would be used to study energetics and dynamics of the coupled ITM system on a global scale for the first time. Although EOS A and B are also shown, there is actually very little activity in either of these missions addressing ITM science. Finally a major mission, the ITM Coupler/ENA Imager, is shown later in the first decade of the 21st century and is intended to study the global distribution of electric fields, thermospheric winds, intermediate plasma layers, EUV/UV radiation, etc., in a coordinated manner, together with the distribution and dynamics of charged particles in the magnetosphere utilizing an ENA imager. The ITM Coupler/ENA Imager represents the centerpiece of the program in this discipline area.

The fourth panel shows activity in the cosmic and heliospheric physics area. There is significant effort in this discipline area beginning in 1990 with the launch of the Ulysses spacecraft and the anticipated operation of the ISTP/Wind and SAMPEX spacecraft. SAMPEX is part of the Small Explorer program. Another approved program is the Advanced Composition Explorer (ACE) that is expected to operate into the early part of the 21st century. The centerpiece in this discipline area is the Solar Probe, expected to be launched around the year 2000 and to provide data during its solar passage through the latter part of the first decade. Finally the Ultra-Heavy Collector (UHCR) mission is shown and is expected to be an intermediate class mission. At the end of the planning horizon, spending will have been initiated for the Interstellar Probe which is shown as collecting data after about

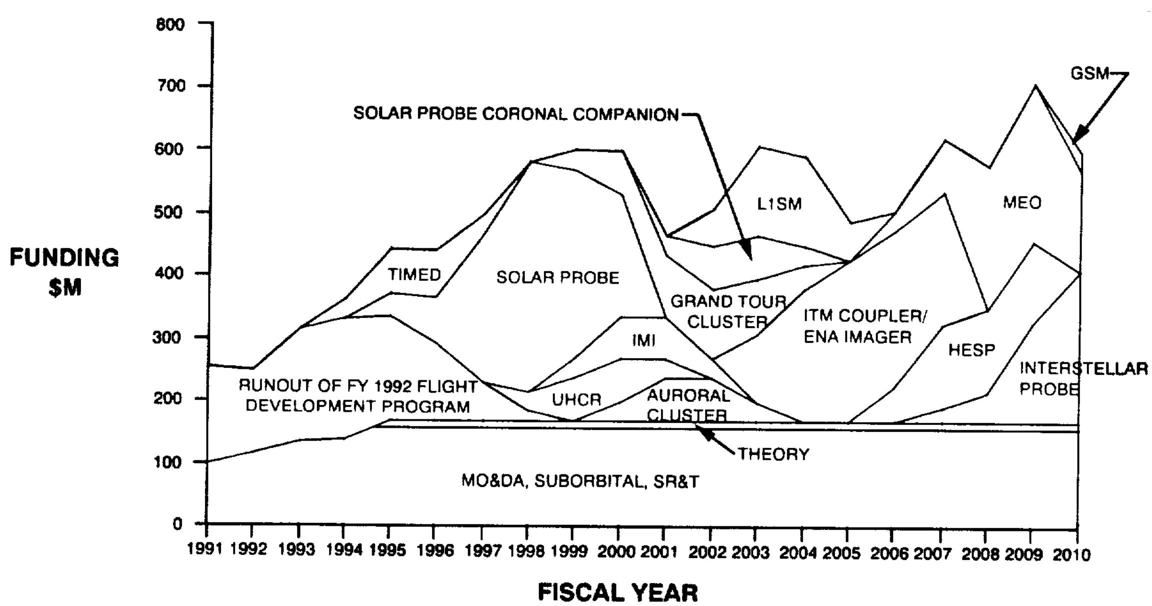


Figure 3-2. Annual funding requirements of consensus scenario without SEI, constant 1990 dollars. Note that funds for the Explorer Program are not included here. Explorer funds are provided from the Astrophysics Program.

2012. Throughout this entire interval, it is expected that data will continue to be accumulated in the outer heliosphere from the Pioneer 10 and 11 spacecraft (through the year 2000) and from the Voyager 1 and 2 spacecraft through the end of the planning period. Below the fourth panel are shown the future Explorers for all of the space physics disciplines, to be selected by competition anticipated via Announcements of Opportunity (AO).

The time sequence of missions shown in Figure 3-1 reflects the budget priorities decided upon as an appropriate and evolving level of activity in the space physics discipline. These priorities are shown in Figure 3-2 for the period 1991 to 2010. In building up this particular timeline it was necessary to begin with the funding level of the Space Physics Division in fiscal 1991, include new starts originally considered in the OSSA plan for Fiscal Year 1992, i.e., OSL and Astromag, and continue the currently approved programs through their completion in the mid-90's. This is shown as the runout Fiscal Year 1992 flight development program, which peaks at about $325 M by 1995. Beginning in 1994, it is recommended that the TIMED mission start with a launch by 1998, while a new start for the Solar Probe in 1995 is shown for that time interval, as currently envisioned in the OSSA Strategic Plan. The combined spending of the currently planned program, together with the Solar Probe, pushes up the level of effort to ~ $600 M by 1998. It was concluded by the study group that such a level would be the likely share of the Space Physics Division in an OSSA budget that is anticipated to be in the range of about $5 billion by that time. New starts in 1998 are also anticipated for the Grand Tour Cluster, the IMI, and the UHCR which, together with a later start for the Coronal Companion, begin to pick up the wedge created by the decrease in funding of the Solar Probe. Later the Auroral Cluster and the L1SM mission continue while a start of the ITM Coupler/ENA Imager begins in the year 2002, building up to a launch by 2007. By 2005 the Mercury Orbiter program begins with an anticipated launch late in the decade. At the same time, activity on HESP begins for a launch in time to overlap the anticipated solar maximum activity from 2009 to 2011. Finally, the Interstellar Probe new start at 2007 begins to

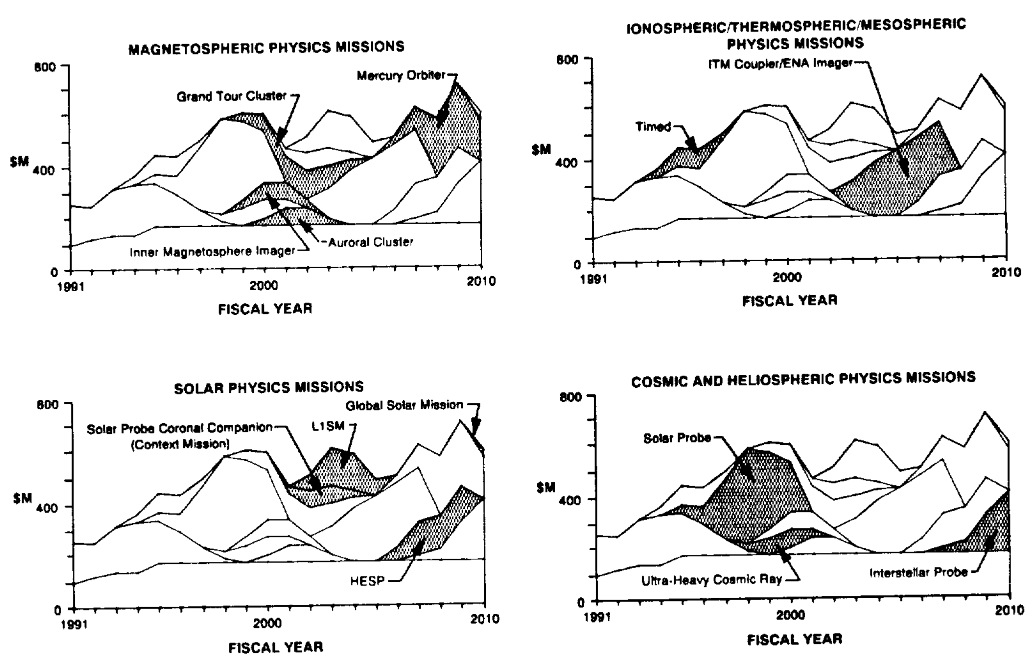


Figure 3-3. Missions of the four space physics disciplines for the consensus scenario without SEI

provide the coverage of the last frontier in the beginning of the 21st century with a fast probe to the heliosphere boundary. As is evident from the preceding chart, the prime phase of spacecraft data taking will not occur until the year 2012.

It should be noted that, given the current plans for flight activity of space physics spacecraft in the early 90's, the expected level of mission operations and data analysis (MO & DA), plus suborbital programs and space research and analysis (SR & T) should add to approximately $160 M per year. This level, together with a theory program, represents a baseline which is the lowest budget level necessary for the continued viability of the Space Physics Division and its associated community of scientists. As the chart indicates, however, it is a tacit assumption that the MO & DA activities of the programs to be initiated in the mid-90's will be accommodated within the levels already established for the ISTP missions. This assumption needs to be re-examined, after a detailed study of the data

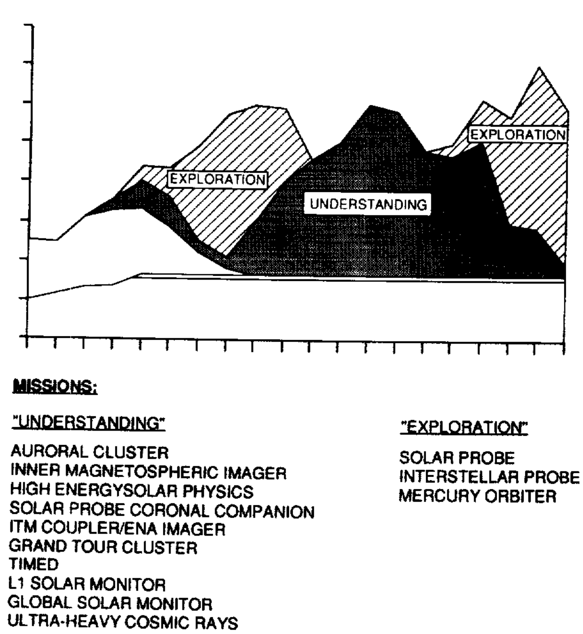


Figure 3-4. Thematic funding distribution of the consensus scenario without SEI

reduction and analysis requirements of each of the proposed missions. The results of such a study are not available at the present time. As was stated earlier, the part of the Space Physics Division's program that is funded by the Explorer line item in the OSSA budget is not specifically included in this planning effort because that program is managed by the Astrophysics Division. It is specifically assumed, however, that the Space Physics Division will continue to have access, on an equitable basis, to resources from the Explorer program for the foreseeable future.

At this point we may ask to what extent our original intention to balance the space physics program among the various disciplines was achieved by this timeline. Figure 3-3 shows in four panels the same timeline shown in Figure 3-2, but shaded for those regions that are covered by projects in the particular discipline area. Clearly, there is significant activity in each of the discipline areas, although this presentation understates the degree of activity in a given discipline because programs that relate to more than one discipline are only shown in one of the four panels. An example is the Solar Probe, which serves both the cosmic and heliospheric and solar physics disciplines, but is only shown in the cosmic and heliospheric area. An area of some concern is the ITM discipline, where there is a lapse of activity following the TIMED mission before the ITM coupler comes into existence. This apparent lack of activity is due to the necessity of addressing the global distribution of fields and other parameters of the ITM system in a very comprehensive fashion that utilizes a large number of spacecraft. It was felt by the community that such a major program needed the experience to be gained from TIMED in order to develop the techniques and community for a project of this magnitude.

Another way of assessing the question of whether the plan addresses the principal criteria of exploration and understanding is shown in Figure 3-4. Here the funding curve is added depending on whether each of the projects principally addresses "Understanding" or "Exploration." It is evident that the plan has a significant component of exploration work initially, followed by programs that address more detailed issues of understanding and then again followed at the end of the planning horizon by programs that address exploration. Thus, it would appear that our original aim of addressing the themes of exploration and understanding in most of the discipline areas has been largely accomplished.

A most important aspect of the strategy has been to make certain that not only are the missions selected representative of the principal scientific thrusts, but that the underlying theory and associated tools are developed concurrently so as to maximize the scientific productivity of the program. The Theory Panel, working together with the discipline panels, has assured the integration of missions, tools, and principal scientific thrusts into coherent themes that address theoretical problems of true intellectual significance. This interrelationship is shown in Figure 3-5.

This figure illustrates in chart form the way in which the mix of missions relates to basic space physics theory research. This chart lists a number of overarching theoretical themes which are identified within one or more of the four disciplines of space physics. It then indicates for each mission the potential contribution to increased understanding related to the individual themes in the noted discipline or disciplines. The fact that the themes cut across discipline boundaries reflects the underlying unity of space physics theory.

Some of the themes are self-explanatory (e.g., Nature of Flows and Turbulence, Acceleration of Particles, Transport, Coupling of Micro and Macro Scales, Coupling of Local and Nonlocal Dynamics, and Evolution of Matter). Structures in Space refers to the problem of understanding the self-organization of plasmas into coherent cellular structures, such as the heliospheric and magnetospheric boundaries, plasmaspheres, plasma sheet, and such other elements as plasmoids, flux ropes, auroral arcs, and boundary layers. The formation of such structures is an outstanding and challenging problem for space physics theory.

The chart is also intended to indicate which of

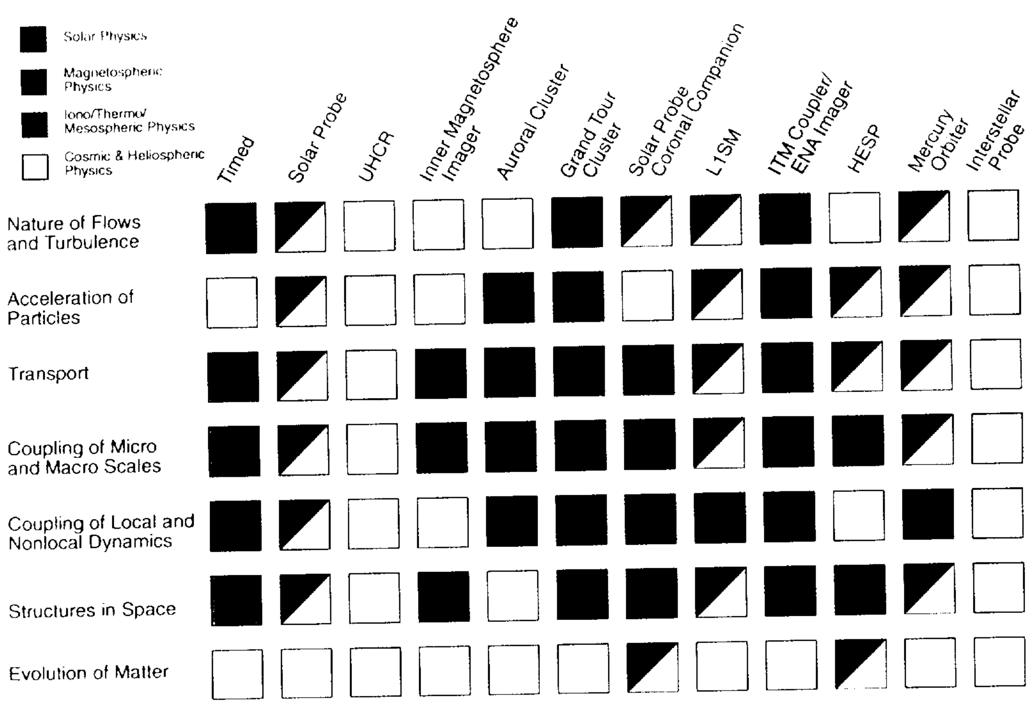


Figure 3-5. Theoretical thrusts of future missions

the missions contemplated will provide crucial new data that are relevant to these themes, and, of course, also to suggest that theoretical research in these themes can enhance the various missions. Thus, themes go beyond mission-related theory. A key point of the chart is that, in most cases, the themes are relevant to many disciplines and many missions.

3.2 Consensus Scenario with SEI

If the Space Exploration Initiative (SEI) program were approved, a number of solar missions that could perform a monitoring function and constitute part of the base program would naturally become elements of it. This recognition enables the base program to be rearranged somewhat as shown in Figure 3-6. The principal difference between this figure and Figure 3-1 is that the L1SM mission does not appear any longer in the early part of the decade. This change, together with the relegation of the Auroral Cluster to the Explorer program, enables some rearrangement of missions, especially the start of the Mercury Orbiter program closer to the year 2000, in line with the expressed preference of the magnetosphere community. The remainder of the program remains largely unchanged, with some small adjustments such as the move of the UHCR mission to later in the decade and introduction of the Solar Polar Orbiter as the sole element of the GSM not transferred to the SEI program.

These changes are reflected in the funding chart shown in Figure 3-7, showing that the overall cost of the program ranges from $500 to $600M by 1998. The general comments made in the scenario without SEI, i.e., regarding the Explorer Program and the uncertainty in the MO & DA line, also apply to the funding profile shown in Figure 3-7. The funding profiles with SEI, broken down by

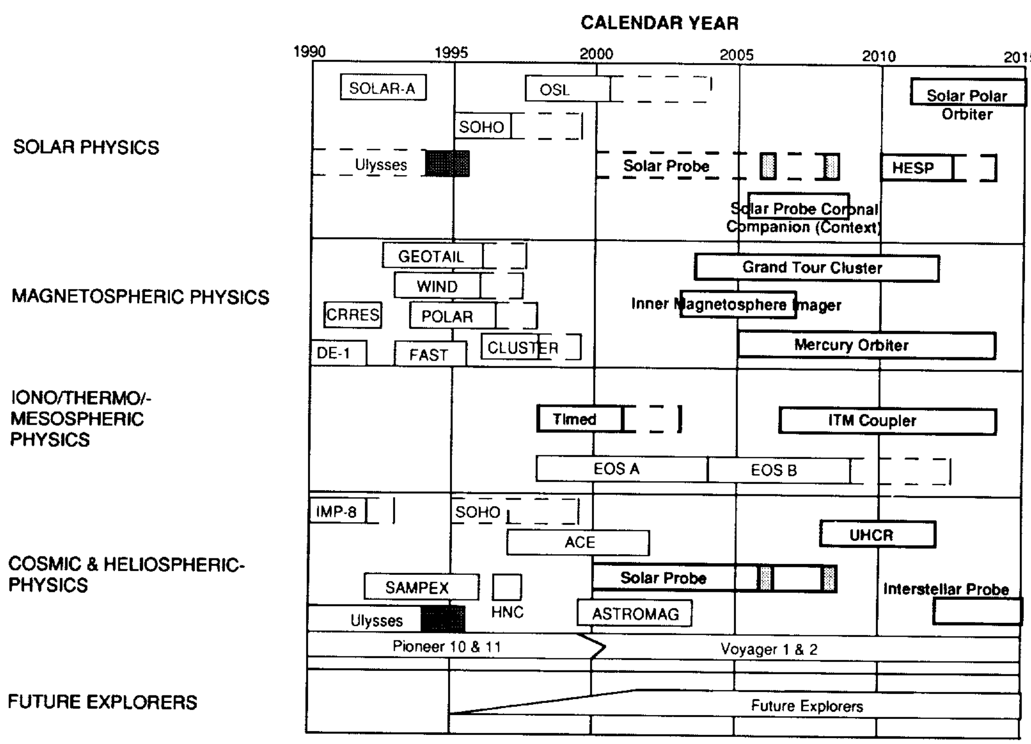


Figure 3-6. Timeline of the consensus scenario with SEI for the period 1990 to 2015

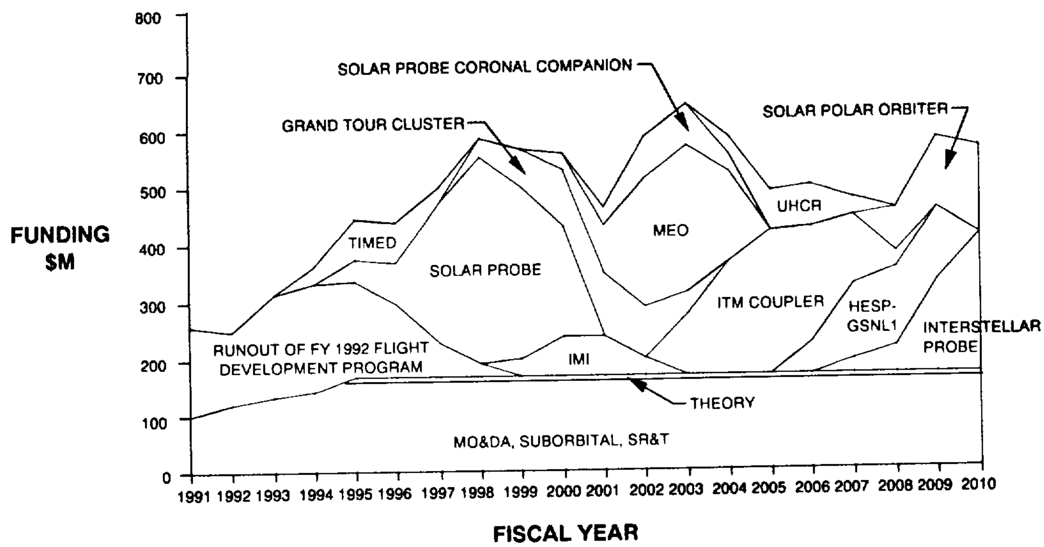


Figure 3-7. Annual funding requirements of consensus scenario with SEI, constant 1990 dollars. Note that funds for the Explorer Program are not included here. Explorer funds are provided from the Astrophysics Program.

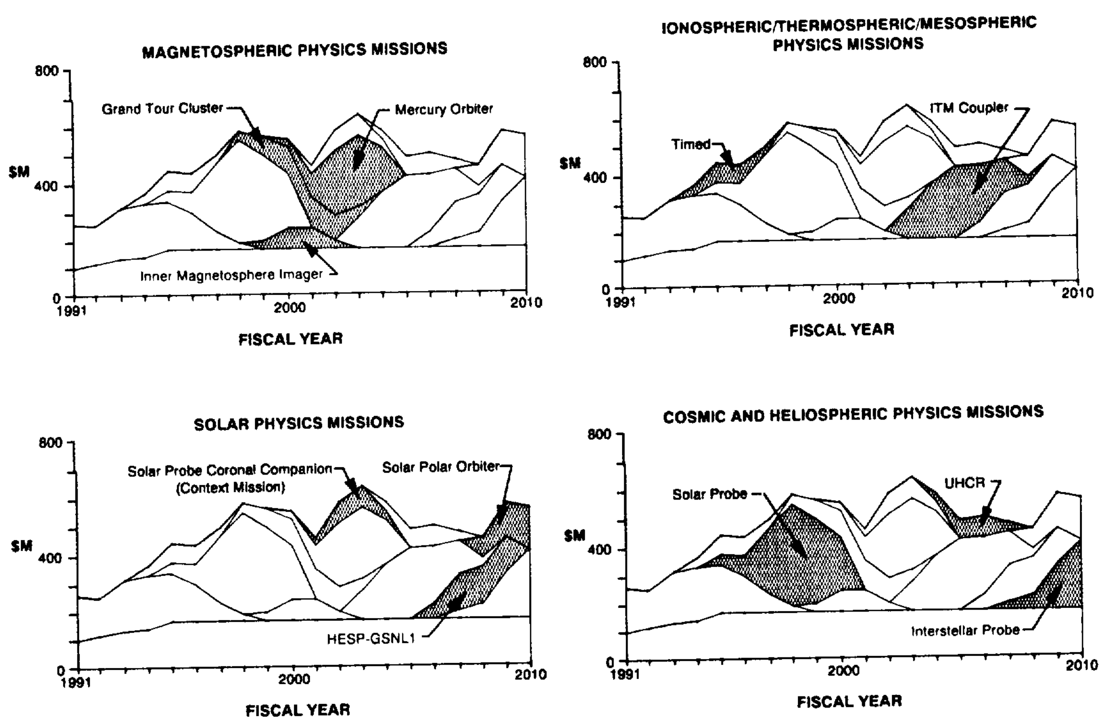
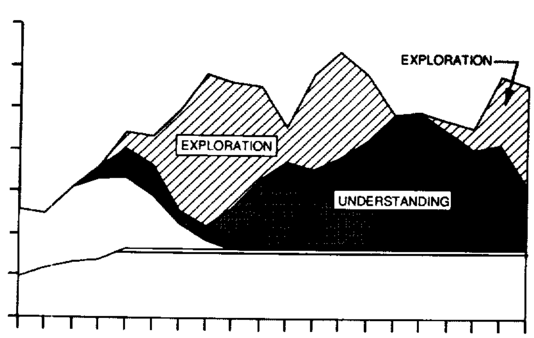


Figure 3-8. Missions of the four space physics disciplines for the consensus scenario with SEI

discipline, are shown in Figure 3-8. As was the case with the earlier scenario, there is significant activity in most disciplines for a good part of the planning horizon. Here again, the solar physics area is complemented by the data obtained from the Solar Probe, which is included in the cosmic and heliospheric mission profile. Finally, Figure 3-9 shows the program broken down according to the classifications of "Understanding" and "Exploration," and we see that both of the themes are being addressed throughout most of the planning period.

A way to visualize the progression of the base program without SEI and the elements that contribute to it is shown in Figure 3-10. Here the list of baseline programs in the four separate discipline areas is shown at the left with time progressing down and to the right, in the direction of the arrows. Enabling science for SEI includes solar monitors spaced at 120° intervals surrounding the Sun at 1 AU, and such other programs as the Mars Aeronomy Observer, a program that is necessary to investigate the aeronomy of Mars prior to aerobraking maneuvers and the landing of human explorers. The Space Exploration Initiative foresees a lunar base and a Mars outpost. It is possible to conceive of a number of unique scientific observations that can only be performed on the lunar surface, as listed on the lower right of the figure. Thus, the elements of space physics science in connection with SEI are (a) enabling science that is necessary for the implementation of the SEI program and (b) unique science that can only be done at a lunar base.



MISSIONS:

"UNDERSTANDING"

INNER MAGNETOSPHERIC IMAGER
HIGH ENERGYSOLAR PHYSICS GSM/L1
SOLAR PROBE CORONAL COMPANION
ITM COUPLER
GRAND TOUR CLUSTER
TIMED
SOLAR POLAR ORBITER
ULTRA-HEAVY COSMIC RAYS

"EXPLORATION"

SOLAR PROBE
INTERSTELLAR PROBE
MERCURY ORBITER

Figure 3-9. Thematic funding distribution of the consensus scenario with SEI

Our study did not have sufficient time to define and scope a fully developed program for SEI, nor were the missions considered fully scoped in terms of cost and schedule. However, a panel of the study group did consider the full range of SEI-associated programs and has composed a funding scenario similar to those shown in Figures 3-2 and 3-7. This scenario is shown in Figure 3-11 and foresees activities beginning in Fiscal Year 1995, on the assumption that the SEI program is to start in Fiscal Year 1991. Several elements are included, both enabling science and unique science, plus other elements that can be accommodated on Space Station Freedom such as a second generation Astromag, for example. The overall funding level of the program is between $300 and $400M a year. A further break-down of the costs shown in Figure 3-11 is given in Figure 3-12, where the elements of the Space Station Freedom program, enabling Science, and Unique Science are shown separately. A list of the programs and their principal objectives is given in Table 3-2. Because of the lack of extensive study, it is not possible to ascribe the same level of certainty, thoroughness, and scrutiny that was possible for the programs described in Figures 3-2 and 3-7. Additional work will be necessary if further definition of this program is desired.

3.3 General Comments

One of the most important aspects of the study is that the group provided a strong reaffirmation of the Solar Probe for a Fiscal Year 1995 new start, as presently called for in the OSSA Strategic Plan. The Solar Probe is viewed as a "flagship" mission for space physics, and as such it represents the centerpiece of the over-all plan for the Space Physics Division. The group also recognized the

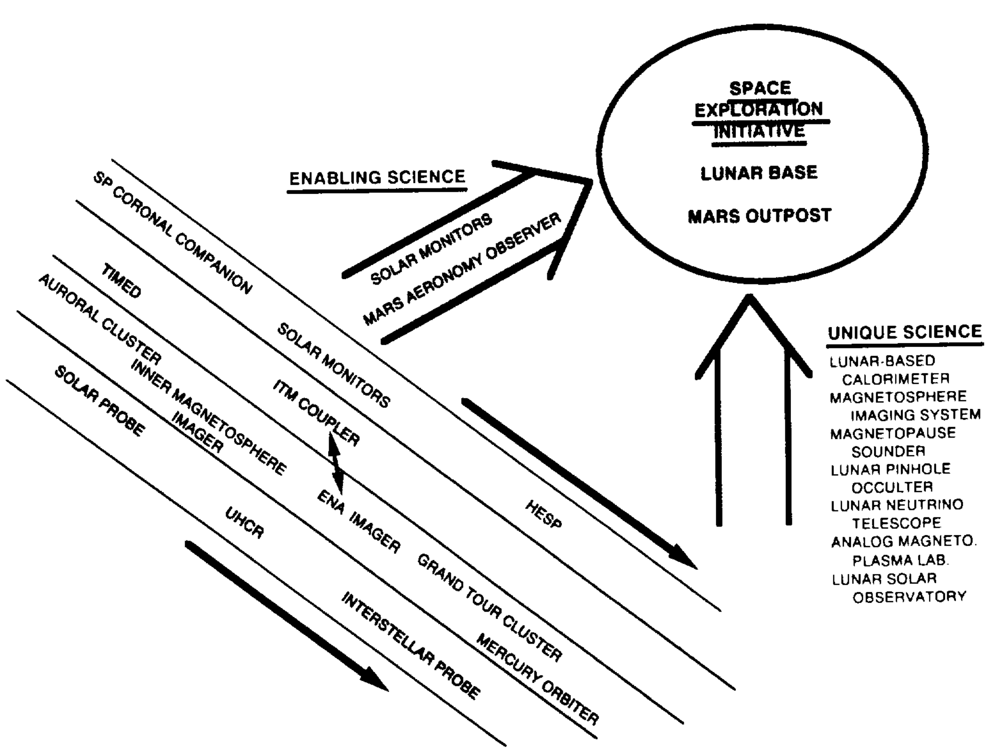


Figure 3-10. Progression of consensus scenario without SEI to support of an SEI program.

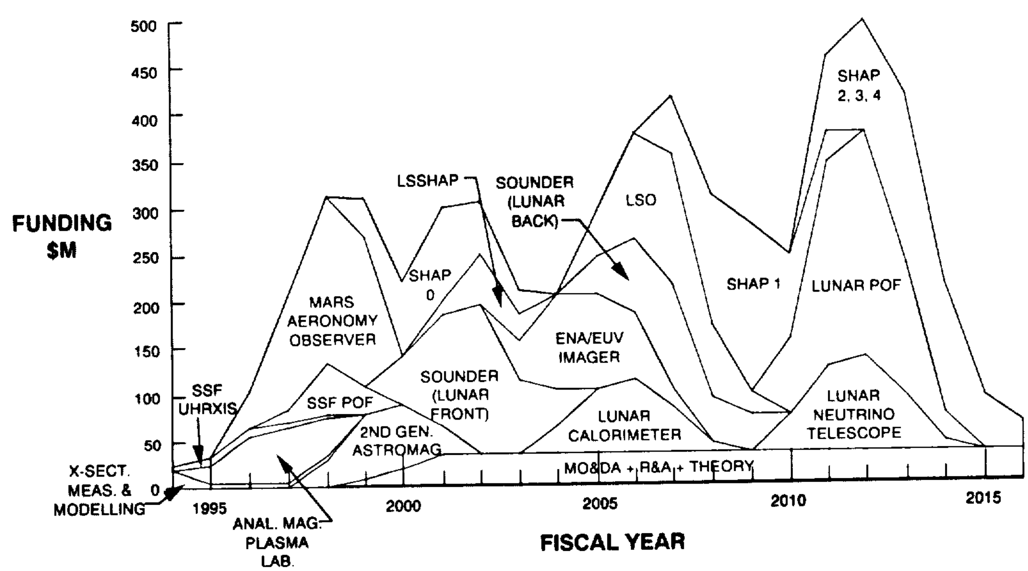


Figure 3-11. Composite SSF- and SEI-funded space physics projects, both "enabling" and "unique science"

importance of correlative *in-situ* measurements with remote observations from Earth orbit—hence the Solar Probe Coronal Companion context mission. The concomitant conclusion is that carefully focused advanced technology development activity is required to support the solar probe for a Fiscal Year 1995 new start.

The study also gave considerable attention to the Explorer program, funded and managed by the Astrophysics Division on behalf of all of OSSA but of particular significance to space physics. Delta-class Explorers historically have been a central element of NASA space physics activity since Explorer 1, and one of the two now approved for development is a space physics mission (Advanced Composition Explorer—ACE). The new Small Explorer (SMEX) program is especially important to space physics for addressing focused objectives on a rapid time scale, for achieving discipline balance, and for maintaining program continuity and capability. Indeed, in the first SMEX competition, eight space physics-related proposals were rated Category 1, and two of the first three missions selected for development are space physics missions (Fast Auroral Snapshot Explorer [FAST] and Solar, Anomalous, and Magnetospheric Explorer [SAMPEX]).

In the study, two specific Explorer program recommendations have been made: (a) to increase the rate of Delta-class Explorer missions started after 1999 (to which point the program is already committed), and (b) to transfer the SMEX program management to the Space Physics Division. The latter change would have the salutary effect of

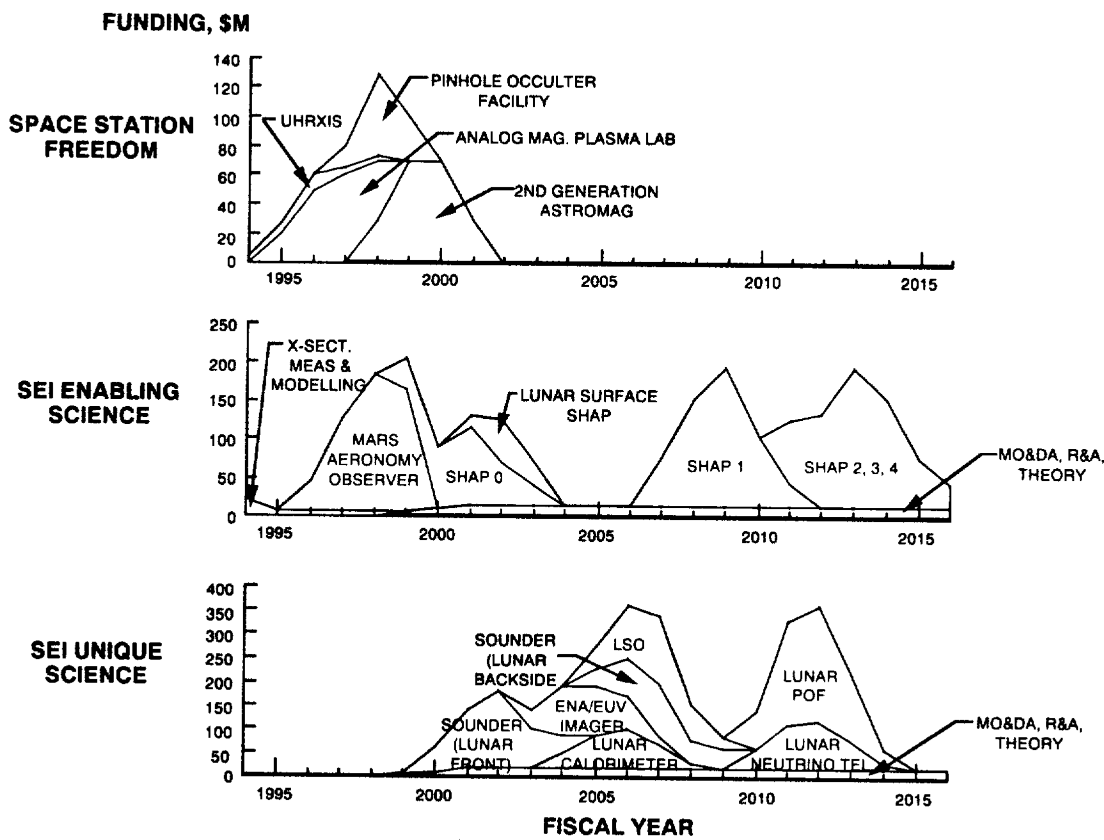


Figure 3-12. Separate SSF, SEI enabling science, and SEI unique-science space physics projects

providing programmatic flexibility to each division for Explorer spacecraft that are most suitable to that division's needs and would enable each to plan its own Explorer program activity in a more comprehensive manner.

Finally, the technical study teams, working in concert with the science discipline teams, have identified a number of areas where advance in the level of technology would contribute to mission enhancement, either through an increase in mission capability or in probability of success. This list of relevant technology advances is described in Appendix A.

PROGRAMS	DESCRIPTION
Space Station Freedom	
SSF UHRXS (Ultra-High Resolution Extreme Ultraviolet Spectroheliograph)	**High resolution spectroscopy of extreme ultraviolet lines for the study of the solar chromosphere, corona, and corona/solar wind interface.**
SSF POF (Pinhole Occulter Facility)	Solar particle acceleration and coronal physics using aperture-encoding grids and occulting masks at great distances from the detectors and telescopes.
Analog Mag. Plasma Lab.(Analog Magnetospheric Plasma Laboratory)	**Simulation of and experiments in the magnetosphere induced by the magnetic field generated by ASTROMAG moving through background ionospheric plasma.**
2nd Generation ASTROMAG	Reflight of ASTROMAG facility with next-generation instruments for study of isotopes at higher energies, higher resolution study of antiprotons and positrons, and searches for antimatter with increased sensitivity.
Level 1: SEI Enabling Science	
X-Sect. Meas. & Modelling (Cross-Section Measuring and Modelling)	**Measurements of heavy element interaction cross sections and yields. Propagation studies of cosmic radiation through materials and study of shielding requirements for humans in long-duration space missions.**
MAO (Mars Aeronomy Observer)	Characteristics of the thermosphere, ionosphere, and mesosphere of Mars, effects of interaction with the solar wind, and diurnal and seasonal atmospheric variations. This information is critical to the development of Mars aerobraking concepts.
SHAP 0 (Solar Hazard Assessment and Prediction)	**Initial monitor of the sun, probably from Earth orbit, to study the sun and solar activity for the purposes of increasing ability to assess and predict radiation hazard to humans in long duration space flight and warning of predicted and observed solar events.**
LSSHAP (Lunar Surface SHAP)	Solar Hazard and Assessment Prediction systems on the lunar surface to improve predictive capability and to monitor solar activity in support of human exploration of the moon.
SHAP 1 (Solar Hazard Assessment and Prediction)	**First element of the in-ecliptic network of solar monitors to study the sun and monitor solar activity both for predicting solar events and assessing their effects and for warning of impending and observed events.**
SHAP 2, 3, 4 (Solar Hazard Assessment and Prediction)	Subsequent elements of the in-ecliptic network placed at various locations appropriate to warning humans on Mars and in transit to and from Mars.
Level 2: SEI Unique Science	
Sounder (lunar frontside)	**Active sounding of the magnetopause boundary, plasma gradients in the magnetopause boundary layer and boundary motions, magnetosphere waveguide propagation characteristics, and structure and dynamics of the magnetotail from the Earth-facing lunar surface.**
LSO (Lunar Solar Observatory)	Observations of the structure and dynamical behavior of the solar magnetic field, photosphere, chromosphere, corona and solar flares across the energy spectrum.
Sounder (lunar backside)	**Active sounding of the magnetosphere and magnetopause from the lunar back side, with emphasis on the magnetotail.**
ENA/EUV Imager (Energetic Neutral Atom/ Extreme Ultra-Violet Imager)	Imaging of the magnetosphere, plasmasphere, plasmasheet, and magnetotail for global magnetospheric configuration and dynamics; observation of substorm and storm effects.
Lunar-based Calorimeter	**Composition, acceleration mechanisms, and sources of high energy cosmic rays above 10^{15} eV.**
Lunar POF (Lunar Surface Pinhole Occulter Facility)	Hard X-ray observations to gain understanding of rapid non-thermal energy releases in the solar corona and sources of cosmic hard X-rays.
Lunar Neutrino Tel. (Lunar-based Neutrino Telescope)	**Diffuse flux of heavy neutrinos, directional flux of weakly interacting massive particle (WIMP) annihilation products, and sources of cosmic neutrinos free of "background" from interactions in the Earth's atmosphere.**

Table 3-2. Space Station Freedom, SEI enabling, and SEI unique-science missions and their respective principal objectives

4.0 Cosmic & Heliospheric Physics

The Cosmic and Heliospheric Physics Program for the years 1995 to 2010 is centered on two themes:

- The next frontier: the global heliosphere and interstellar space
- Cosmic particle acceleration and the evolution of matter

The first of these themes includes a bold new program of exploration, spearheaded by two Frontier Probes, Solar Probe and Interstellar Probe, which will explore the boundaries of the heliosphere from a few solar radii to beyond 200 AU, including a significant penetration into local interstellar space. Solar Probe will carry out direct measurements of plasma, fields, and energetic charged particles, neutrons, and gamma rays in the outer regions of the corona from an orbit extending to within 3 solar radii of the Sun's surface in order to investigate the structure and dynamics of the corona and the acceleration of the solar wind and solar flare particles. Interstellar Probe will explore the detailed structure of the solar wind termination shock and heliopause, investigate the interaction between the heliosphere and interstellar medium, and then explore the nature of the interstellar medium itself by providing the first comprehensive *in-situ* studies of the plasma, fields, energetic particles, gas, and dust in nearby interstellar space.

The second theme will be addressed by missions that will probe cosmic acceleration processes on scales from interplanetary to interstellar space, extending comprehensive studies of energetic cosmic and heliospheric particles to the heaviest elements in the periodic table and some of the highest energy particles in the Galaxy. These missions include an Ultraheavy Cosmic Ray Spectrometer for nuclei from Z=30 to Z=100, and a series of Explorer missions to measure the isotopes of ultraheavy solar and galactic nuclei, low-energy cosmic ray antiprotons and positrons, solar wind turbulence and associated particle acceleration, and the composition of cosmic rays from 10^{13} to 10^{15} eV. If a manned lunar base is established it will permit construction of a Lunar-Based Calorimeter to investigate the composition and origin of cosmic rays near the "knee" in the spectrum at ~10^{16} eV, as well as a Lunar-Based Neutrino Telescope for astrophysical sources. Additional significant advances can be achieved through collaborative ventures with other disciplines on a variety of interplanetary missions that include Mercury Orbiter, Solar Polar Orbiter, and a solar observing mission in low-Earth orbit to complement Solar Probe.

These missions build on the current Cosmic and Heliospheric Physics Program and extend it with significant thrusts in a number of new directions. Over the next two decades they will play leading roles in carrying out the interwoven themes of exploration and understanding that characterize the consensus program for space physics.

4.1 Introduction

The heliosphere is a vast region extending from the Sun to interstellar space. It is created by the continuously expanding corona, or solar wind, which forces out interstellar magnetic fields and plasma to distances of ~100 AU (See Figure 4-1).

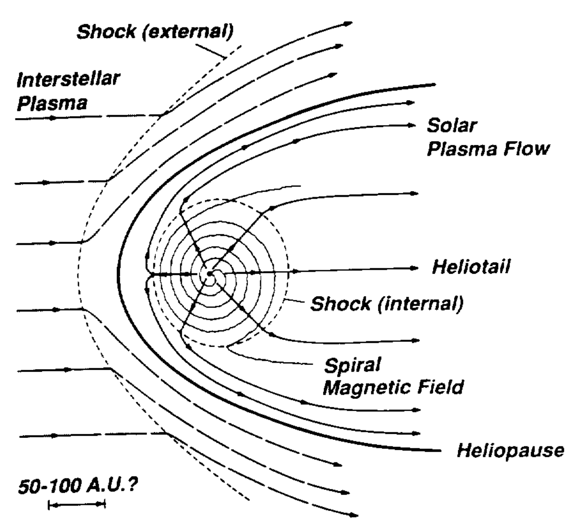


Figure 4-1. Schematic illustration of a plausible structure for the heliosphere, showing the solar-wind termination shock, the contact surface or heliopause, and the incoming interstellar gas

Among the multitude of diverse phenomena occurring in the heliosphere is the acceleration of energetic particles at sites that include solar flares, traveling and corotating interplanetary shocks, comets, and the solar-wind termination shock. Of the energetic particles observed, those with the highest energy are the galactic cosmic rays, which are accelerated beyond the heliosphere, elsewhere in the Galaxy, most likely by very similar processes.

The NASA Cosmic and Heliospheric Physics Program for the early 1990's is centered around extended exploration of the heliosphere, on-going investigations of the solar wind and solar energetic particles, and continuing studies of plasma, particles and fields in the interplanetary medium and cosmic rays from the Galaxy, using data from previous interplanetary missions and the existing fleet of the following currently operating spacecraft:

- Pioneer 10 & 11
- Interplanetary Monitoring Platform (IMP-8)
- Voyager 1 & 2
- International Comet Explorer (ICE)
- Ulysses

In addition, there are currently operating cosmic and heliospheric instruments carried on Galileo and CRRES. The Global Heliospheric Study planned for implementation in the early 1990's will advance the correlative analysis of observations from this constellation of spacecraft and the understanding of the structure of the heliosphere and the many physical processes influencing its evolution and dynamics. During the coming years increasing emphasis will be placed on the development and launch of the following approved missions:

- *SAMPEX*—A Solar, Anomalous, and Magnetospheric Particle Explorer to be launched as part of the Small Explorer Program to measure low-energy particles from a polar orbit.

- *ACE*—An Advanced Composition Explorer to measure the elemental and isotopic composition of H to Ni nuclei over six decades in energy/nucleon, from solar wind to galactic cosmic ray energies.

- *Astromag*—A superconducting magnetic spectrometer including powerful instruments that will extend particle and anti-particle spectroscopy into the GeV and TeV energy ranges.

- *HNC*—A Heavy Nuclei Collector designed to measure the abundances of the heaviest elements in the periodic table.

- *POEMS*—A Positron/Electron Magnetic Spectrometer for the Earth Observing System that will measure electrons and positrons from the Galaxy and the Sun, and also solar gamma-rays and neutrons.

In addition, the continuing Cosmic and Heliospheric Physics Program also includes: instruments to be carried on the WIND, NOAA-I, and SOHO missions; a vigorous balloon-flight program to develop and test new instrumentation, and to initiate new investigations of cosmic ray elements, isotopes, antiprotons, and positrons; an accelerator-based program for testing and calibrating new detectors and for measuring nuclear cross sections critical to astrophysics; and an extensive theoretical program to study fundamental interactions of heliospheric and interstellar plasma, energetic particles, and fields.

The program for 1995 to 2010 described in this report is an extension of the ongoing program and the recently approved missions listed above. Should plans for these missions change, highest priority should be given to developing other options for accomplishing the continuing program.

Most of the elements of the Cosmic and Heliospheric Physics Program presented in this report are based on two reports from earlier planning exercises that took place just before this Strategy-Implementation Study. The first of these, *The NASA Cosmic Ray Program for the 1990's and Beyond,* by the Cosmic Ray Program Working Group, resulted from a workshop held at Goddard Space Flight Center in November 1989, while the second, *Heliospheric Science in the 1990's,* is the result of a series of meetings held in 1989 by the Heliospheric Program Working Group. At the first workshop for this study in January 1990, the efforts of these two communities were melded into a single, coherent program (see "The NASA Cosmic and Heliospheric Physics Program for 1995 to 2010" in the document, *Space Physics Strategy-Implementation Study, Volume 1: Goals, Objectives, Theory*).

Several other activities have also occurred during this time. The Solar Probe Science Study Team has reported the results of a pre-Phase-A study of this mission in their November 1989 report, *Solar Probe: Scientific Rationale and Mission Concept.* In March 1990 an Interstellar Probe Workshop was held which resulted in the report *The Interstellar Probe: Scientific Objectives and Requirements for a Frontier Mission to the Heliospheric Boundary and Interstellar Space.* In addition, a workshop was held in April 1990 to further define the requirements for the Ultraheavy Cosmic Ray Spectrometer. Finally, during the first half of 1990, JPL, GSFC, MSFC, and SAIC conducted technical feasibility studies of Solar Probe, Interstellar Probe, and two lunar-based instruments.

4.1.1 Scope and Themes

In order to build on the current program described above, and assure that progress continues into the years 1995–2010, two major themes emerge:

- The next frontier: the global heliosphere and interstellar space

- Cosmic particle acceleration and the evolution of matter.

The first of these themes, which recognizes that progress in essentially all areas of heliospheric and space physics is most effectively accomplished by direct exploration, will be spearheaded by two frontier probes: Solar Probe and Interstellar Probe. The second theme recognizes that particle acceleration is ubiquitous in nature, and that comprehensive studies of accelerated particles can provide information on the origin and history of a variety of samples of matter. It will be addressed by missions that will probe cosmic acceleration processes on scales from interplanetary to interstellar space, including new instrumentation that will span the elements of the periodic table, and extend to some of the highest-energy particles in the Galaxy.

4.1.2 Scientific Objectives

Cosmic and heliospheric physics is concerned with studies that can be conveniently grouped under the following topics:

- The origin, structure, and evolution of the solar wind

- The interaction of the heliosphere, the solar wind, and the interstellar medium

- Fundamental microscopic and macroscopic plasma processes

- The acceleration and transport of energetic particles

- The origin and evolution of matter

Recent progress in addressing these goals has been due in large part to two key developments: the exciting exploratory discoveries of Pioneer and Voyager in the outer heliosphere, aided by theoretical interpretations; and—in the case of cosmic ray physics—by the exposure of sophisticated new particle spectrometers in space and on balloons. However, as a result of the significant decrease in launch opportunities during the 1980's, many new advances in instrumentation have not had opportunities for space flight. Fortunately, a vigorous cosmic and heliospheric program is planned for the 1990's, including several new missions that will accelerate progress in a number of key areas.

4.2 Proposed New Cosmic and Heliospheric Missions

At the Bethesda workshop of this planning study, a consensus Space Physics Program for the years 1995–2010 was developed that satisfied a wide range of requirements including scientific urgency, interdisciplinary balance, and perceived

Frontier Probes to Explore the Global Heliosphere and Interstellar Space
- A Solar Probe to make *in-situ* measurements of the Sun's corona
- An Interstellar Probe to the heliospheric boundary and interstellar medium

Missions to Investigate Particle Acceleration and the Evolution of Matter
- An Ultraheavy Cosmic Ray Element Spectrometer for nuclei with $30 \leq Z \leq 100$
- An Explorer for Ultraheavy ($Z \geq 28$) Solar/Galactic Isotopes
- A Solar Wind Turbulence/Particle Acceleration and Transport Explorer
- A Matter/Antimatter Explorer for antiprotons, positrons, electrons, and antinuclei
- A High Energy Composition Explorer for 10^{13} to 10^{15} eV cosmic rays

Space Exploration Initiative
- A Lunar-Based Calorimeter to measure cosmic ray composition to $\sim 10^{16}$ eV
- A Lunar-Based Neutrino Telescope for detecting sources of cosmic neutrinos

Collaboration on Missions with Other Disciplines
- Mercury Orbiter
- Global Solar Mission
- Solar Probe Coronal Companion

Table 4-1. New cosmic and heliospheric physics missions for the years 1995 to 2010

budgetary limitations. The program was developed with two options, one that assumed that the Space Exploration Initiative (SEI) would be evolving concurrently with this program, and one that assumed it would not. For the Cosmic and Heliospheric Physics Branch, the two options are similar; both include the following three cosmic and heliospheric missions:

- *Solar Probe*—A mission to within 3 solar radii of the Sun's surface to provide observations *in situ* of the plasma, energetic particles, fields, and dust of the solar corona, and detailed studies of coronal structure and processes of solar wind plasma and particle acceleration.

- *Interstellar Probe*—A mission to ≥200 AU designed to explore the outer heliosphere, cross the solar wind termination shock and heliopause, and provide detailed measurements of interstellar plasma, fields, dust, and cosmic rays.

- *The Ultra-Heavy Cosmic Ray Spectrometer (UHCR)*—An Intermediate mission designed to provide accurate measurements of cosmic ray nuclei from Z=30 to Z=92 and beyond; including cosmic ray "clocks" in the actinide region.

The timeline for conducting these missions is shown in Figure 4-2, which also includes missions

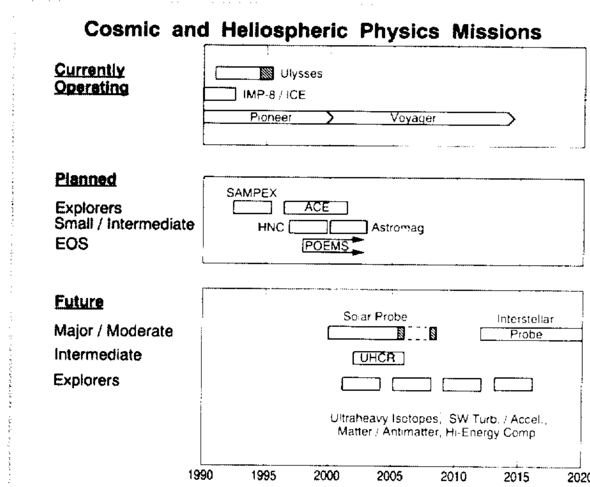


Figure 4-2. Cosmic and Heliospheric Physics missions that are currently operating, planned, and proposed for the future. The time scale for UHCR in the bottom panel is for the program option without SEI; in the option that includes SEI, UHCR is delayed by an additional six years.

from the current and planned program. Table 4-1 summarizes these and other elements of the Cosmic and Heliospheric Program, including programs for SEI and the Space Station, additional Explorer-class missions that have been identified to address key scientific objectives, and missions proposed by other disciplines where collaborative ventures are possible. Section 3 contains more detailed descriptions of these missions.

4.2.1 *Proposed New Large Cosmic & Heliospheric Missions*

4.2.1.1 Solar Probe

The heliosphere is dominated by the extension of the solar corona into the solar wind, yet our knowledge of the mechanisms that heat the corona, shape its structure and accelerate the solar wind is far from complete. This limitation on our understanding is due to the ambiguities inherent in observational techniques which up to now have carried out only remote sensing studies of the corona, and *in-situ* observations to about 60 solar radii (R_s). Resolving these ambiguities requires *in-situ* particle-and-fields observations close to the Sun. Solar Probe is a bold mission to explore regions to within four solar radii of the Sun, and provide a quantum leap in our knowledge of the corona. The mission concept calls for a Jupiter flyby after which the probe plunges towards the Sun in an orbit which passes over both solar poles and reaches a perihelion over the solar equator at 4 R_s, as shown in Figure 4-3. This perihelion falls well inside the extent of the expected turbulence envelope of the Sun. A propulsive maneuver 10 hours after the first perihelion will result in a second flyby after a period of 2.5 years, greatly enhancing the science return of the mission.

The investigations to be carried out on the Solar Probe Mission will fill gaps in our current understanding of the extended solar corona including mechanisms for (i) coronal heating and transport, (ii) acceleration of the solar wind, and (iii) transient processes. Thus, the mission will address the physical processes that help shape the many different forms of the solar corona, drive the solar wind, and accelerate a small percentage of solar particles to very high energies. In addition, Solar Probe will perform the first exploratory measurements of the near-Sun dust environment, which is currently controversial.

To carry out these studies requires a payload including plasma and plasma-wave experiments, a magnetometer, thermal and suprathermal ion mass and charge analyzers, medium and high energy particle experiments, a coronal spectral imager, a neutron/gamma-ray experiment, and a dust experiment. In addition, an X-ray spectrometer is currently under investigation for inclusion in the strawman payload. All of these experiments have a successful flight heritage, and since the spacecraft design utilizes a carbon-carbon heat shield that will maintain a 25–30 degree (C) operating environment, no significant new instrument development is required.

The scientific return from Solar Probe will be enhanced by the simultaneous flight of a mission in low-Earth orbit (Coronal Companion) that will provide remote sensing studies of the corona during the two or more Solar Probe flybys.

The Solar Probe mission has undergone a pre-phase-A study and is presently included in the Office of Space Science and Applications (OSSA) *Strategic Plan*. Throughout it has remained the

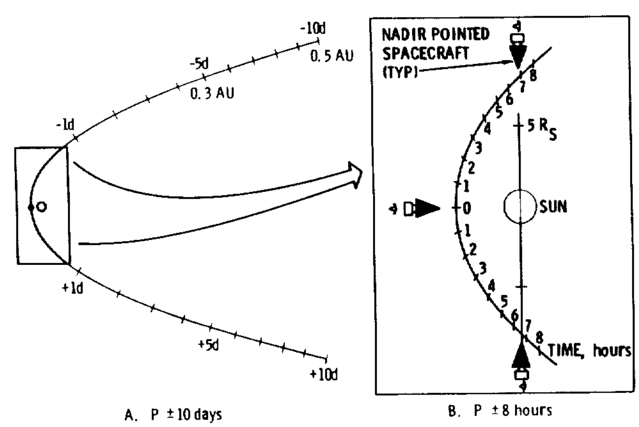


Figure 4-3. Solar Probe near-perihelion trajectory

highest-priority new mission in the Space Physics Strategy-Implementation Study. If given a new start in 1995, Solar Probe could be ready for launch in the year 2000.

4.2.1.2 Interstellar Probe

In our present view of the large-scale structure of the heliosphere (see Figure 4-1), the solar wind flows radially outward to a "termination shock," which is surrounded at somewhat greater distance by the "heliopause," which is the boundary between the solar wind and interstellar plasmas. A bubble of solar wind thereby shields the inner heliosphere from the plasma, energetic charged particles, and fields of the interstellar medium; to observe these one must get outside the heliopause.

The primary goals of the Interstellar Probe would be to explore the outer heliosphere, cross the solar wind termination shock and heliopause, and make a significant penetration into interstellar space, thereby providing the first comprehensive studies *in situ* of the plasma, energetic particles, fields, gas, and dust in the nearby galaxy. In broad terms, the scientific objectives of Interstellar Probe will be to: (1) explore the nature of the interstellar medium and its implications for the origin and evolution of matter in the galaxy; (2) explore the structure of the heliosphere and its interaction with the interstellar medium; and (3) explore fundamental astrophysical processes occurring in the heliosphere and interstellar medium. Thus, for example, Interstellar Probe will permit a comparison of the elemental and isotopic composition of the local interstellar gas with that of (unmodulated) galactic cosmic rays, and it will provide *in-situ* measurements of particle acceleration at the solar wind termination shock over many decades in energy.

Although the size of the heliosphere is uncertain, present estimates place the termination shock and the nose of the heliosphere at ~100 to 150 AU from the Sun. It is possible that one or more of the Voyager or Pioneer spacecraft may well locate the termination shock and return valuable exploratory data within their lifetimes. Interstellar Probe will greatly extend these pioneering ventures by providing detailed, comprehensive measurements with modern instrumentation specifically designed to observe the boundary of the heliosphere and the interstellar medium itself.

At an Interstellar Probe workshop held during the course of this study, a strawman payload was identified that included instruments to study elemental and isotopic composition of the interstellar plasma, suprathermal ions, anomalous cosmic rays, and galactic cosmic rays; three-dimensional analyzers of the solar wind and interstellar plasma dynamics; the distribution and composition of interplanetary and interstellar dust; UV and IR sources; interstellar cosmic-ray electron, positron, and nuclei spectra; interplanetary and interstellar magnetic fields and plasma waves; and gamma ray bursts. The vast majority of these instruments can be based on existing technology that has or will have been flown on earlier missions. It is likely that additional instrumentation appropriate to this exploratory mission will be identified.

The goal of the Interstellar Probe would be to reach a minimum distance of 200 AU within 25 years, requiring spacecraft velocities of ~10 AU/year. Although this requirement will be a challenge, preliminary studies by JPL have shown that reasonably sized spacecraft can achieve such velocities by utilizing trajectories that combine planetary gravity assists with a powered solar flyby. For such trajectories, Interstellar Probe would benefit from Solar Probe technology. During the coming years it is also likely that advanced propulsion systems such as solar sails may enable even greater spacecraft velocities.

4.2.2 Proposed New Interdisciplinary Collaboration Missions

The following missions, advocated primarily by other disciplines, offer unique opportunities for addressing the objectives of cosmic and heliospheric physics if appropriately instrumented, or they offer significant opportunities for interdisciplinary studies.

4.2.2.1 Mercury Orbiter

The Mercury Orbiter (MeO) mission, proposed by the magnetospheric community, includes in its strawman payload both solar-wind and magnetic-field instruments which would provide a continuous, several-year data base for studying solar-wind evolution at 0.4 AU. In addition, if appropriately instrumented, MeO offers a unique opportunity for obtaining solar energetic-particle (SEP) observations that can decisively answer long-standing, fundamental questions about the flare process and the solar corona. For large solar flares, MeO can determine whether particles observed in interplanetary space are energized; e.g., in the lower corona versus in extended shocks which accelerate particles out to many solar radii. For small, impulsive flares, MeO's close location to the Sun will make it possible to time the injection of energetic particles to 1–2 minutes, giving critical constraints for particle-acceleration models. Data on neutron and gamma-ray detectors on MeO will, when compared with energetic particle data, give further insights not obtainable from observations at 1 AU.

4.2.2.2 Global Solar Mission

This mission would include two or more ecliptic spacecraft and one Solar Polar spacecraft at relatively high inclination to the ecliptic plane which would be devoted primarily to solar-physics remote sensing studies but, with suitable instruments, could also carry out systematic exploration of the high-latitude solar wind, magnetic field, and energetic particles, thus building on the initial reconnaissance to be carried out by Ulysses. The high-latitude heliosphere is expected to differ significantly from the equatorial regions due to the effects of solar rotation, and experience gained in in-ecliptic studies shows that systematic observations over an extended period will be required to gain an understanding of the high latitude regions and their coupling to such features as polar coronal holes.

4.2.2.3 Coronal Companion

The Solar Probe Coronal Companion, an Intermediate-class mission in low-Earth orbit with remote sensing imaging and spectroscopic measurements, will provide critical data on the solar atmosphere at the time when the Solar Probe flies close to the Sun. While the Solar Probe will provide detailed *in-situ* particles-and-fields measurements close to the Sun, Coronal Companion will provide remote sensing data on the lower solar atmospheric sources of the outflowing plasma sampled by the Solar Probe. The mission includes UV/EUV/white-light coronagraphs to sample the corona from the solar surface to several tens of solar radii; and a EUV/XUV and/or soft X-ray instrument to image the low coronal structure on the disk.

In addition to the above, there are other missions where simultaneous observations or collaborative studies could benefit two or more disciplines. For example, experience with SMM has shown that studies of solar energetic-particle events at (or inside) 1 AU conducted simultaneously with the solar flare X-ray, gamma-ray, and neutron studies to be carried out by HESP, or by a Small Explorer with more limited instrumentation, would enhance our understanding of the flare phenomenon.

4.2.3 *Proposed New Intermediate Cosmic & Heliospheric Missions*

4.2.3.1 An Ultraheavy Cosmic Ray Spectrometer for Nuclei with $30 \leq Z \leq 100$

Measurements of the abundances of cosmic rays beyond the "iron peak" are of special interest because of the information these "ultraheavy" (UH) nuclei carry about the neutron-capture nucleosynthesis processes that have forged elements in the upper two thirds of the periodic table, and because they include a number of radioactive species that can be used as "clocks," particularly among the "Actinide" group of elements that include Th, U, and possibly trans-uranic nuclei.

The relative abundances of elements from H to U in cosmic rays are summarized in Figure 4-4. Because of the relative rarity of UH nuclei, there are at present measurements of only even-Z nuclei from Z=30 to 60, and only element groups for Z>60, including only two nuclei in the Th-U region ($Z \geq 90$). The HNC experiment selected for Space Station Freedom would expect ~40 actinides (with a sizable uncertainty) in a four-year exposure using passive track detectors. The next step beyond

HNC, requiring an order-of-magnitude increase in collecting power, would provide accurate measurements of the clocks in the actinide region, giving the "age" of these heavy nuclei since nucleosynthesis. In addition, high-resolution measurements of all elements from Z=30 to 82 would provide information on r-process and s-process nucleosynthesis, and on the propagation history of these heavy nuclei.

It presently appears that the best approach for achieving the required increase in collecting power would be an array of electronic detector modules in an orbit where they spend most of their time outside the magnetosphere.

4.2.4 Proposed New Small Cosmic & Heliospheric Missions

Although the primary focus of this Strategy-Implementation Study has been on new missions in the major, moderate, and intermediate categories, the Cosmic and Heliospheric Panel also identified significant Explorer-class missions that are required for continued progress in this discipline. Indeed, because these smaller missions were felt to be so essential for addressing focussed objectives on a rapid time scale, for achieving discipline balance, and for maintaining program continuity and capability, the panel recommended that approximately one third of the total budget be devoted to small missions. Even if intermediate missions are included in this category, this goal can be reached only if there are expanded opportunities for Explorer missions, including Small Explorers (SMEX's). Each of the following would cost less than one year of the Explorer budget.

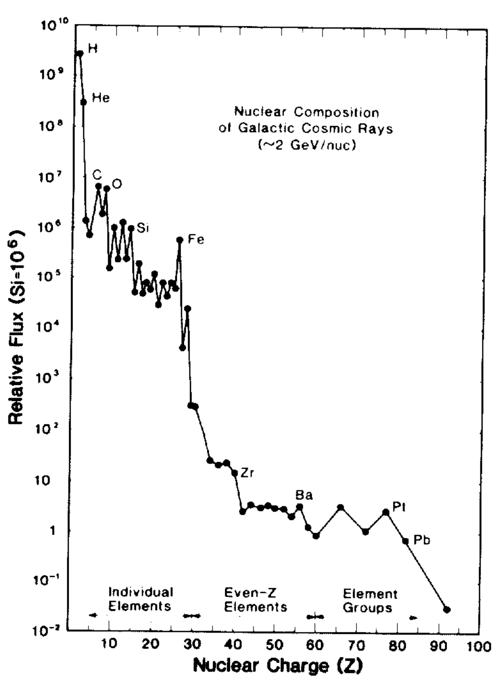


Figure 4-4. Present knowledge of the elemental composition of galactic cosmic rays, including the ultraheavy nuclei with $Z \geq 30$

4.2.4.1 Trans-Iron Solar and Galactic Isotope Explorer

Currently approved investigations of the isotopic composition of energetic heavy nuclei will explore in depth the nucleosynthesis of solar and galactic elements from H to Ni ($1 \leq Z \leq 28$). The extension of isotopic composition studies to ultraheavy elements ($Z \geq 30$) will allow investigation of neutron-capture nucleosynthesis processes responsible for nuclei beyond the Fe peak (see Figure 4-4). The Trans-Iron Solar and Galactic Isotope Explorer would provide the isotopic abundances of both galactic cosmic rays and solar energetic particles to allow comparison of recently synthesized galactic matter with solar system abundances at the time of formation of the solar system. The detailed study of UH isotopes will require exposure outside the magnetosphere of new large-area sensor systems that can be based on extensions of detectors now under development for ACE and for balloon experiments.

4.2.4.2 Solar-Wind Turbulence/Particle Acceleration Explorer

Particle acceleration processes are best studied by *in-situ* observations. This mission would consist of two or more identically-instrumented spacecraft separated by variable distances (≤ 0.1 AU), each designed to investigate hydromagnetic turbulence and associated energetic-particle acceleration in the interplanetary medium. Located, for example, at the sunward Lagrangian point, these spacecraft would measure: (1) the statistical properties of the plasmas and magnetic field, (2) particle phase-space densities for electrons, protons, and alpha particles, and (3) the acceleration of particles at shocks which propagate past the spacecraft. The complex coupling between magnetohydromagnetic parameters and subsequent particle acceleration studies would require an integral theoretical component throughout the mission.

4.2.4.3 A Matter/Antimatter Explorer (MAX)

One attractive explanation for the so-called "dark matter" that apparently constitutes more than 90% of the total mass of the universe invokes supersymmetric (SUSY) particles, produced in the Big Bang, which may now populate our galactic halo in great abundance, and annihilate each other to produce low-energy antiprotons. A definitive search for evidence of these decay products will require a measurement sensitivity many times greater than can be achieved with balloon experiments. The Matter-Antimatter Explorer would place a high-field permanent-magnet spectrometer in an orbit outside the magnetosphere to search for low-energy antiprotons and primordial anti-helium with a sensitivity goal of one part in 10^8. These low-energy measurements from ~0.1 to 1 GeV/nuc would complement those planned at higher energy (from ~1 to 10^3 GeV) by Astromag.

4.2.4.4 A High-Energy Composition Explorer

Direct measurements of the energy spectra and elemental composition of cosmic ray nuclei at very high energies are needed to investigate particle acceleration in supernova-driven shocks and the storage of high energy particles in the galaxy, and to search for spectral difference between different species in the composition of high energy particles. The High-Energy Composition Explorer would measure the elemental composition of cosmic rays with 10^{13} to 10^{15} eV per particle using ionization calorimetry and transition and Cerenkov radiation detectors. Among other objectives, this mission would overlap with and therefore calibrate the new generation of ground-based air-shower detectors.

4.2.5 Proposed Space Station Freedom Attached Cosmic & Heliospheric Missions

In 1989 two cosmic and heliospheric experiments, Astromag, the superconducting magnetic spectrometer facility, and the Heavy Nuclei Collector (HNC), were selected for flight as attached payloads on Space Station Freedom. The experiments selected for initial use of Astromag would between then measure (i) the spectra of cosmic-ray anti-protons, positrons, electrons, and individual heavy nuclei at energies from ~4 to ~10^3 GeV, with measurements of some abundant species approaching ~10^{15} eV/particle; (ii) search for evidence of primordial antimatter; (iii) extend cosmic-ray isotope measurements to energies of several GeV/nucleon; and (iv) study high-energy nuclear interactions. As a result of the recent decision to suspend funding of attached payloads, a free-flying version of Astromag that would accomplish most of its high priority objectives is now under study.

The HNC would be use passive glass-track detection to measure the elemental composition of cosmic-ray nuclei from Z ~ 50 to Z ~ 96. Because HNC is a passive experiment that requires only very limited resources, it may still be suitable for flight on Space Station.

4.2.6 Proposed Space Exploration Initiative (SEI) Associated Cosmic & Heliospheric Missions

4.2.6.1 Enabling SEI Science

Solar Flare and Cosmic Ray Monitoring/Prediction. If human beings are ever to spend prolonged periods in space, either on a lunar base or en route to other planets, it will be necessary to have improved knowledge and predictability of the fluxes of solar-flare particles and galactic cosmic rays, and the radiation hazard they represent to man. Currently planned missions, such as ACE, Astromag, and POEMS, will provide the required measurements of the spectra of heavy cosmic-ray nuclei and their solar-cycle variations. One approach to the solar flare problem would use a network of spacecraft such as the Global Solar Mission, which consists of one spacecraft in a high-inclination orbit to the ecliptic, and additional in-ecliptic spacecraft at different phase offsets (e.g., at 90, 180, and 270 degrees) from Earth. Particles-and-fields instrumentation on these spacecraft would allow monitoring of radiation fluences and occurrence rates from all solar longitudes, and would be essential in providing real-time warning to a lunar base or to astronaut crews during voyages to Mars. By combining remote-sensing measurements of solar active regions and transient phenomena such as coronal mass ejections, improved predictive capability for the onset and magnitude of solar energetic particle events would be achieved.

4.2.6.2 Enabled SEI Science

Lunar-Based Calorimeter. This instrument would measure the spectrum and composition of cosmic rays with energies of 10^{15} to 10^{17} eV, where ground-based measurements of air showers have found a distinct change in slope or "knee" in the all-particle energy spectrum, suggesting that nuclei with > 10^{16} eV may have a fundamentally different origin and composition than at lower energies. To measure the composition and energy spectrum of 10^{16} eV cosmic rays with reasonable precision requires a calorimetric approach, with a collecting power of ~500 m^2sr year. Although the required several-hundred-ton mass of such a calorimeter would be prohibitive for an orbiting instrument, on the moon the bulk of the calorimeter material could be compressed lunar regolith; only relatively light plastic scintillators or drift tubes, electronics, and support structure would be carried up from Earth.

Lunar-Based Neutrino Telescope. It would have as its principal goal a search for diffuse fluxes of neutrinos that could address the "missing mass" question. These include either massive neutrinos, or neutrinos resulting from the annihilation of Weakly Interacting Massive Particles (WIMP's) that have been postulated by recent theories. For these (and perhaps other) potential sources of diffuse neutrino fluxes, the "background" flux on the moon may be up to 10^3 times lower than on Earth, because there is no atmosphere. The suggested approach for lunar-based neutrino astronomy would be to place light-weight gas-filled detectors in underground cavities to detect secondary muons resulting from neutrino interactions. The roof of the cavity would provide shielding from cosmic rays, while the floor would provide the target mass for upward-moving neutrinos.

4.2.7 Theory

Because the scientific return of missions can be significantly enhanced by integrating experimental data with theory, it is recommended that interdisciplinary and theoretical studies be an accepted component of all space science missions. Of particular value would be the establishment of a series of several iterative workshops, involving both theorists and experimentalists, focussed on significant scientific problems that become particularly "ripe."

4.2.8 Other Program Elements

The continued health of the community is also critically dependent on the following program elements:

4.2.8.1 Infrastructure and Resources

It is essential for the training of students and young scientists that a scientific infrastructure exist that permits creative work on time scales shorter than that of present space missions. It is therefore imperative that opportunities and resources be available for detector development in the laboratory, Guest Investigator programs on flight missions, short-turnaround observations on suborbital missions such as balloons, and quick access to space as provided by Small Explorers.

4.2.8.2 Tracking of Interplanetary Spacecraft

Tracking of many of the growing armada of operating spacecraft by the Deep Space Network (DSN) is woefully inadequate at present, and this tracking shortfall is expected to increase during the next few years. It is therefore imperative that NASA provide for effective communication of

OSSA tracking requirements, investigate possibilities for international cooperation in tracking, and consider upgrading the DSN to maximize the science return from current and future missions.

4.2.8.3 Balloon Program

Balloon-lofted experiments remain an indispensable component of the cosmic ray program that: (i) provides significant scientific results in a very cost-effective manner; (ii) supports the development and testing of new techniques and instrumentation; and (iii) plays an indispensable role in the training of students and young scientists.

4.2.8.4 Accelerator-Based Studies

The Bevalac heavy-ion accelerator at Lawrence Berkeley Laboratories has become an essential facility for providing detailed measurements of nuclear cross sections required to interpret cosmic-ray measurements, and by SEI, and for providing facilities to test and calibrate new instrumentation. If the Bevalac shuts down in 1994–1995 as anticipated, it will be important for NASA to obtain access to other appropriate accelerator facilities.

4.3 Discussion

While the discussion above has been limited to those missions that address the goals of cosmic and heliospheric physics, the Consensus Space Physics Program includes a large number of other missions that address a wide range of additional goals. The Cosmic and Heliospheric Physics Panel enthusiastically endorses this program. We find that it satisfies the requirements of balance with respect to discipline participation, scientific goals, and mission size. It combines a broad spectrum of exciting mission concepts into a unified program that can lead to major progress on several fronts.

The Cosmic and Heliospheric Physics Panel is particularly enthusiastic about the exploratory elements of the consensus program. This theme of exploration will be spearheaded by our two frontier probes, Solar Probe and Interstellar Probe, which between them will explore the limits of the heliosphere. Each of these missions has the compelling scientific rationale, the exciting technical challenge, and the bold sense of adventure that justify the resources required by major missions of this kind. Missions such as MeO and the Global Solar Mission also offer opportunities for exploring the large scale heliosphere. In addition, instruments such as the Lunar-Based Calorimeter and the Lunar-Based Neutrino Telescope that have been proposed for SEI will also offer innovative opportunities for exploration as they probe boundaries of another nature.

A second unifying theme in the consensus program is understanding, exemplified by the Ultraheavy Cosmic Ray Spectrometer that will extend comprehensive composition studies to the upper two-thirds of the periodic table, and by a number of the Explorer concepts that have been identified. For many problems, understanding can be accelerated by interdisciplinary collaboration and coordination, and the Solar Probe, Coronal Companion, MeO, Global Solar Network, and HESP missions all provide such opportunities to varying degrees. In the above examples, the object of study is the Sun, or its influence over the interplanetary medium, a subtheme that unites many of the proposed missions.

Overall, the consensus program is composed of what appears to be a reasonable balance of mission sizes. In the case of cosmic and heliospheric physics, however, most of the resources are concentrated in the two frontier probes. As a result, it is particularly important for this community to maintain access to small missions such as Explorers, Small Explorers, and possible flights of opportunity, preferably through an expanded Explorer Program. Although this Strategy-Implementation Study has quite properly concentrated on large missions ranging from ~$200 million to more than a billion dollars in cost, frequent access to space is and will continue to be the most important requirement for a healthy cosmic and heliospheric physics community. One of the new elements of the proposed Space Physics Program is the introduction of a new intermediate class of missions with costs of up to $200 million. While there appears to be a clear requirement and rationale for this new mission class, and the Ultraheavy Cosmic Ray Spectrometer is one such example, in cosmic and heliospheric physics there is an equally important requirement for additional Explorer-class missions in the $50-100 million category.

It is important to keep in mind that the Cosmic and Heliospheric Physics Program that has been presented here for implementation during 1995 to 2010 represents a continuation and extension of the ongoing program, and its purpose and priorities assume the successful completion and launch of recently selected missions, such as ACE, Astromag, HNC, and POEMS. If plans for these already approved missions change, such as has happened recently for Astromag and HNC, highest priority should be given to accomplishing the objectives of these missions by alternate means.

5.0 Ionosphere/Thermosphere/ Mesosphere Physics

The Ionospheric-Thermospheric-Mesospheric (ITM) Physics Program of research for the years 1995 to 2010 will focus on the development of a globally self-consistent theoretical and empirical understanding of the ITM as a single, electrodynamic, chemically-active, and kinetically-reactive multi-constituent system of particles, fields, and currents. The investigative plan requires that the understanding be global, cover the full spectrum of solar-terrestrial conditions and associated coupling mechanisms, and encompass quiescent and dynamic conditions carried to the limit of highly irregular and unstable modes. The program ultimately seeks a predictive capability for the responses of the system as a whole to naturally-occurring solar-terrestrial controls and to anthropogenic effects.

Two themes have been selected for specific activities within the ITM Program. These are:

Exploration of the mesosphere and lower thermosphere/ionosphere.

Investigation and understanding of the coupling and dynamics within the ITM system itself and its coupling to the heliosphere and magnetosphere above, and to the lower atmosphere below.

These themes directly relate to the thematic concepts of "Exploration" and "Understanding" that characterize the overall Consensus Program for the Space Physics Division and provide the framework for the specification of the two primary ITM missions.

Implementation of the first theme involves an innovative program of exploration of the upper mesosphere and lower thermosphere/ionosphere—a critical transition region sometimes referred to as the "Ignorosphere" because of the paucity of available data. Supporting this theme, the "intermediate" class TIMED mission (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics) will carry out the first comprehensive spaceborne investigation of planetary-scale composition, energetics, and dynamics in the upper mesosphere and lower thermosphere/ionosphere, complementing the NASA UARS (stratospheric) and ISTP (magnetospheric) missions.

The second theme involves the essential step of *synthesis* in our understanding of the ITM system as a whole. This theme will be addressed by a multi-spacecraft mission with comprehensive instrumentation and broad observational coverage designed to investigate the couplings both within the ITM domain and with the stratosphere below and the heliosphere/magnetosphere above. This multi-spacecraft "major" mission, called the ITM Coupler, has as its primary objective a detailed quantitative understanding of the coupling terms in the solar-terrestrial system, including controlling interplanetary, magnetospheric and lower atmospheric forcings, and overall seasonal, solar cycle, LT/UT, and storm-time responses of charged and neutral populations and their global-scale distributions.

Significant advances in the area of ITM physics will also be made through collaborative ventures with other disciplines on missions such as UARS, ISTP, the Inner Magnetosphere Imager, the Grand Tour Cluster, and the Auroral Cluster. Necessary elements of the ITM Program also include a series of focused smaller Explorer missions, balloon and rocket programs, laboratory simulations, and theory.

Implementation of the mission plan will terminate a decade-long hiatus in ITM spaceflight opportunities. The plan provides significant new thrusts for the discipline and implements an important element of complementarity with other SPD and NASA-wide missions in understanding interactive solar-terrestrial processes that impact the responses of the Earth's near-space environment, its effects on man and his systems, and its long-term trends.

5.1 Introduction

5.1.1 Current Understanding of The ITM Domain and its Role in the Solar-Terrestrial System

The Earth's ITM domain has a uniquely important role within the overall solar-terrestrial system. The ITM couples to the magnetosphere and heliosphere above, and to the stratosphere below—responding to solar EUV/UV variations, coronal mass ejections, high-speed streams from coronal holes, atmospheric tides, gravity waves, and lightning storms. It absorbs the bulk of the solar EUV/UV radiation and precipitating-particle energies, and these inputs drive extraordinarily complex photochemical and plasmaphysical processes. It is a region that supports and controls electric currents and potentials ranging up to 10^6 amperes and hundreds of kilovolts, respectively, with exceedingly complicated spatial and temporal distributions.

The ITM is the most complex naturally-occurring plasma domain accessible to combined *in-situ* and remote-sensing diagnostics. It is a region with processes in the continuum, transitional and free-molecular flow regimes. It involves positive and negative ion chemistry, global circulation, kinetics of neutral particle collisions, external and internal electric fields, magnetically-induced anisotropies, and irregularity scale-size distributions from hundreds of kilometers to fractions of a meter. Ion-neutral coupling processes are driven strongly by magnetospheric and solar forcings and, in turn, drive the global electrical circuit, affect the global wind and thermal structures, and electrically couple back into the magnetosphere.

In all cases, ITM responses to coupled internal and external forces are complex and dynamic. Layers move up and down, densities vary dramatically, and composition changes in ways yet to be properly described by empirical or first-principle models. We do not have an accurate understanding of the global time-dependent distributions of electric fields and thermospheric winds, nor the specifications of incident EUV/UV radiation—the primary forces driving the system. We do not understand the physics controlling the mesosphere/lower thermosphere interface, the upward propagation of tides and waves, their ultimate coupling to the ionized constituents, and the cascade of energy between large- and small-scale structures. Within this system we do not know the global distribution of intermediate, sequential, and descending plasma layers, their contributions to critically-important dynamo fields, and the controlling influences of the metallic, atomic, and molecular ion inventory. In the cause-effect chain, we do not understand the interplay of the wind-shear forces and electric fields in the formation of intermediate layers and their control of upper F-region dynamics by fluxtube coupling of dynamo-driven electric fields.

The regions known as the mesosphere and lower thermosphere/ionosphere have been neglected relative to other, more accessible high-altitude domains. The mesosphere and lower thermosphere are too high for balloon platforms and too low for *in-situ* measurements from long-lived satellites. In the mesosphere and lower thermosphere/ionosphere, therefore, the database is sparse and, in many cases, riddled with controversy. The basic state variables of wind, temperature, and composition have not been systematically measured in a global sense, though it is known that complex interactions involving chemistry, dynamics and radiation are responsible for controlling both the mean state and departures from the mean. Tidal structures and gravity-wave breaking processes are known to have a profound, yet poorly understood, influence on the mesosphere. It is likely that there will be anthropogenically-caused, first-order changes in its chemistry, composition, temperature and dynamics within the next two to three decades due to the influence of increasing levels of methane and carbon dioxide. Methane, which is increasing in abundance by 1% to 2% per year, is readily oxidized into water vapor. The consequent increases in mesospheric H_2O will drive stronger HO_x family chemistry with far-reaching effects on ozone and the absorption of energy within the mesosphere. These changes will project their influence upwards into the thermosphere and ionosphere in undetermined ways.

The distribution of charged particles within the mesosphere remains one of the outstanding questions of the lowest-altitude regime of the ITM system. While it is generally agreed that the mesosphere is populated with free electrons and positive and negative cluster ions, reliable measurements and associated theoretical models are non-existent. This lack of information exacerbates the related controversy involving mesospheric electric fields, known to span seven orders of magnitude. Speculations that causal mechanisms are attributable to the existence of charged aerosols have not been proved. These issues are fundamental to the understanding of mesospheric electric-field distributions, current systems, and electrodynamic coupling to the ionosphere.

The physics of the ITM domain and the unknowns listed above are addressed in the ITM Program described herein. The ITM missions are exploratory and focused, addressing the global, dynamic, and coupled system and its role in the solar-terrestrial chain and the near-Earth environment.

5.1.1.1 Historical Perspectives and Related Programs

Previous programs in ITM physics have investigated the individual regions in isolation, but have not developed comprehensive databases, nor have they given proper attention to internal and external coupling processes. We know now that a simplistic view that neglects dynamics and coupling among the various regions is not only incorrect, but misleading. Three most recent Explorer missions attest to this fact. For example, the Atmosphere Explorer (AE) program charted basic thermospheric photochemistry in the 1970's without measuring dynamical interactions or coupling with other regions. Similarly, the Solar Mesospheric Explorer (SME) measured trace-constituent abundances in the mesosphere, but had no dynamical measurements to provide a fully satisfactory interpretation. The Dynamics Explorer-2 (DE-2) program (1981–83), on the other hand, provided a tantalizing glimpse of the richness and variety of dynamical processes in the upper-altitude and higher-latitude part of the ITM system and, in particular, the coupling with the magnetosphere. The spatial and temporal coverage for DE was very limited and the program raised far more questions than were answered. We still do not understand a) the effects of the solar cycle and various dynamic solar phenomenologies, b) the UT/LT, latitude/longitude, and seasonal dependencies, c) the effects of gravity waves and tides, d) the roles of E- and F-region dynamos under static and dynamic conditions, and e) the global impact of the neutral flywheel and fossil winds on ionospheric electric fields and its contributions to high- and equatorial-latitude irregularities.

The UARS mission includes instrumentation with mesospheric capabilities, but the primary focus will be on stratospheric measurements. The principal contribution of UARS to the ITM objectives, therefore, will be to provide information on the lower boundary condition for the ITM. Similarly, the focus of the ISTP mission is on the magnetosphere, with no spacecraft to determine directly the ITM role in magnetospheric processes and the coupling of solar, interplanetary, and magnetospheric processes into the Earth's nearest geospace environment, the ITM. The ISTP mission, therefore, will provide information on the upper boundary condition for the ITM.

While the 10-year hiatus in space flight opportunities for the ITM community has been keenly felt, a vigorous ground-based observational and laboratory measurement program, together with strong balloon and rocket programs, has enabled a combination of experimental and theoretical research to be carried forward. There is clearly an urgent need, however, to re-establish the important spaceborne element for the ITM Program, and this need has been recognized in various national strategic planning documents of the Academy of Sciences.

5.1.1.2 The Planning Process and Unity with NASA and NAS Guidelines

This report summarizes the deliberations of the Ionosphere-Thermosphere-Mesosphere Physics (ITMP) Panel during Workshops 1 and 2 of the Strategy-Implementation Study (SIS) for NASA's Space Physics Division (SPD), held in January and June of 1990, respectively. A series of open meetings and an American Geophysical Union special session at the 1989 Fall Meeting were also conducted to facilitate interaction within the ITM community.

The scientific objectives for the ITM Program and, to some extent, the mission concepts have been formulated in the light of the recommendations of existing strategy documents. For example, the ITM objectives and missions presented in this report are fully consistent with National Academy of Science guidelines *(Space Science in the Twenty-First Century)* and the NASA Office of Space Science and Applications (OSSA) *Strategic Plan of 1989*. The Academy pointed to the study of solar-terrestrial coupling as an important issue, with "emphasis on the response of the system to solar variability." The Academy also pointed out that "to understand better the effects of the solar cycle, solar activity, and solar wind disturbances upon the Earth, we need to: 1) provide simultaneous measurements on many links in the chain of interactions coupling solar perturbations to their terrestrial response, and 2) create and test increasingly comprehensive quantitative models of these processes."

The Academy further pointed out that: 1) "we still do not understand the basic processes that drive and control the behavior of the global electric circuit [and the model of] the ionosphere as a highly conducting equipotential upper boundary is incorrect," 2) "the Earth's mesosphere and lower thermosphere/ionosphere are the least explored regions in the Earth's near space....[Its] overall structure and dynamic responses to magnetospheric substorms, solar flares and stratospheric warnings, and even the basic controlling physical and chemical processes of these effects are not understood."

To study this system, the Academy suggested a multi-spacecraft mission with supporting diagnostics on rocket payloads and ground-based systems.

The objectives of the ITM discipline are also in accord with the NASA OSSA strategy (1989) which looks to: 1) "quantitatively describe the physical behavior of the geospace environment and the effects of solar processes on the Earth," and 2) "establish a set of platforms to study the Earth's system on a global scale...and develop the capability to model the system to predict changes that might occur either naturally or as a result of human activity."

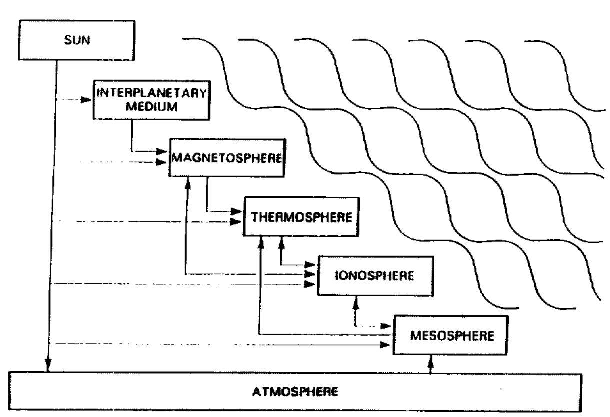


Figure 5-1. Coupling and dynamics in the cascading of particles, fields and waves in the solar-terrestrial environment

5.1.2 Scientific Objectives

The overall scientific objective of the ITM Program is the development of a self-consistent empirical and theoretical understanding of the ionosphere-thermosphere-mesosphere as a single, electrodynamic, chemically-active, and kinetically-reactive multi-constituent fluid that couples to the heliosphere and magnetosphere above and to the stratosphere below. The understanding must be global in nature, must cover the full spectrum of solar-terrestrial conditions and associated internal and external coupling mechanisms, and must encompass quiescent and dynamic conditions carried to the limit of highly irregular and unstable modes.

Within the framework of the overall objective, the issue of coupling takes on a particularly important role. This is illustrated in Figure 5-1, which schematically displays the interactive role of the ITM in the solar-terrestrial system and the various links in the coupling of particles, fields, and waves as energy and momentum are transferred from the Sun to the Earth. If we are to understand the ITM, we must quantify the solar, interplanetary, magnetospheric, and atmospheric controls. We must understand mesospheric/thermospheric coupling due to gravity waves, tides, and trace-constituent transport processes at various scales. We must quantify the electrodynamic coupling between the thermosphere/ionosphere and the magnetosphere, and the processes which control currents, fields, and plasma flows. We must understand the coupling processes between large- and small-scale structures and the effects of turbulence and instabilities on current systems and transport in general. Furthermore, we must understand the coupling between charged and neutral constituents in the ITM system, as that coupling takes place both locally and over large-scale vertical and horizontal domains.

Specific issues addressed in the ITM Program objectives include:

1. The response of the ITM to changes in external energy sources;

2. The mesospheric/thermospheric coupling due to gravity wave, tidal, and trace-constituent transport processes at various scales;

3. The electrodynamic coupling between the thermosphere/ionosphere and magnetosphere, with adequate sensitivity and resolution to evaluate both the forward and backward transfer of energy and mass;

4. The coupling processes between large- and small-scale plasma structures;

5. The consequences of transitions between turbulent and laminar flow and collisional and collisionless media;

6. The long-term trends in the state of the ITM induced by solar-cycle changes and anthropogenic activity;

7. The ozone photochemistry and HO_x, NO_x, and ClO_x catalysis;

8. Trace constituent production in the lower thermosphere, including auroral NO, and subsequent downward transport into the mesosphere;

9. The basic chemistry, kinetics, electrodynamics, and radiative transfer mechanisms in the mesosphere/lower-thermosphere/ionosphere region;

10. The real-time evolution of the global ionosphere electric field in response to solar-wind/magnetosphere coupling;

11. The physics and the impact of mesoscale electrodynamic perturbations on the energy transport and coupling between regions.

The ITM community is poised to carry out this aggressive program. The community has the necessary experience with space platform investigations, a demonstrated capability for the design, fabrication, and testing of comprehensive and innovative ***in-situ*** and remote sensing techniques, and sophisticated numerical codes for simulating various component parts of the ITM system that can be further developed and merged to provide the needed theoretical underpinnings for a truly coupled effort. The information yielded by the missions described in this document will provide a giant step forward in understanding both the ITM system itself and its role in the transfer of energy, momentum, and mass within the solar-terrestrial environment. It will also open the possibility for the development of a predictive capability for changes in the ITM system due to natural and man-made controls.

5.2 Proposed New Ionosphere, Thermosphere & Mesosphere Missions

5.2.1 Scientific Themes

Previous studies of the individual components of the ITM system have clearly indicated that dynamical processes are responsible for the strong couplings that bind the various regions as an interactive whole. Successful previous spaceborne and ground-based programs have delineated, and in some cases quantified, many of the important physical and chemical processes at play in individual regions. We now need to build on the results of previous efforts and design an experimental thrust that recognizes the dynamical and coupled nature of the ionosphere-thermosphere-mesosphere system, including the important connections to the magnetosphere above and to the stratosphere below.

To this end, the ITM Program for the years 1995 through 2010 will focus on the development of a self-consistent theoretical and empirical understanding of the ITM as a single, electrodynamic, chemically-active, and kinetically-reactive multi-constituent fluid that couples to the heliosphere and magnetosphere above and the stratosphere below. The ITM Program requires that the understanding be global, cover the full spectrum of solar-terrestrial conditions and associated coupling mechanisms, and encompass quiescent and dynamic conditions carried to the limit of highly irregular and unstable modes.

This objective sets the stage for an exciting, new and mature phase of scientific endeavor wherein the system ***as a whole*** is treated as a dynamic unit with an intricate network of controls and feedback mechanisms, which we will investigate with a comprehensive measurement program and an associated broad-ranging modeling activity.

Two themes represent specific activities and missions within the newly-proposed ITM Program:

> ***Exploration of the mesosphere and lower thermosphere/ionosphere***

> ***Investigation and understanding of the coupling and dynamics within the ITM system itself and its coupling to the heliosphere and magnetosphere above and to the lower atmosphere below***

The first theme involves an innovative program of exploration of the upper mesosphere and lower thermosphere/ionosphere—a critical transition region sometimes referred to as the "Ignorosphere" due to the paucity of available data. This region is too high for probing by balloons and is generally too low for direct ***in-situ*** satellite sampling. The "intermediate" class TIMED (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics) mission will represent the first comprehensive spaceborne investigation of the planetary-scale composition, energetics, and dynamics in the upper mesosphere and lower thermosphere/ionosphere on a global scale and will complement the UARS (stratospheric) and ISTP (magnetospheric) missions. TIMED will sample the transition region with a combination of ***in-situ*** and remote sensing methods to characterize the global winds, temperatures, and composition, the plasma-ion and electron distributions, the electric fields, and the trace-constituent abundances. Particular attention will be given to determining the critical interchange role played by waves of all scales (planetary-scale waves, tides, gravity waves, and turbulence), electric fields, and particle distributions.

The second sub-theme involves the essential step of ***synthesis*** in our understanding of the ITM system as a whole. This sub-theme will be addressed by a multi-spacecraft mission with comprehensive instrumentation and broad observational coverage designed to investigate physical, chemical, dynamic, energetic, and radiative couplings both within the ITM domain and with the stratosphere below and the heliosphere/magnetosphere above. This multi-spacecraft "major" mission is called the ITM Coupler. It has as its primary objective a detailed quantitative understanding of coupling terms in the solar-terrestrial system, including controlling interplanetary, magnetospheric, and lower-atmospheric forcings and overall seasonal, solar-cycle, LT/UT, and storm-time responses of charged and neutral populations and their global-scale distributions.

5.2.2 TIMED

The intermediate-class TIMED mission will be the first exploratory spaceborne investigation of planetary-scale energetics and dynamics in the critical transition region of the ITM system: the upper mesosphere and lower thermosphere/ionosphere. It will measure the global distributions of plasma particles, fields, winds, temperatures, and composition in the mesosphere and lower thermosphere/ionosphere. It will measure the emissions of trace species in the upper atmosphere, and provide global measurements of NO_x and HO_x and other critical species in the middle atmosphere. The coordinated measurements of electric fields, ionospheric structures, tides, and gravity waves will provide unprecedented coverage and accuracy.

The objectives of the TIMED mission include:

- Determination of a first-order description of the wind, temperature, and composition in the upper mesosphere and lower thermosphere, and the ionospheric composition in the lower ionosphere, with an emphasis on the metallic-ion inventory;

- Characterization of the diurnal, semi-diurnal, and ter-diurnal tides as a function of altitude, and characterization of the spectrum of gravity waves to determine their influence on global circulation and structure;

- Investigation of the interplay among photochemistry, dynamics, and radiative transfer of the mesosphere and lower thermosphere on a regional and global basis;

- Investigation of thermospheric circulation and altitude-dependent storm-time variations in ionospheric and thermospheric parameters;

- Study of conjugacy variations in the ionosphere, fluxtube coupling, and inter-hemispheric responses to dynamic interplanetary and magnetospheric events, including the mapping of dynamo-driven electric fields;

- Investigation of the altitude dependence of irregularity growth mechanisms and plasma energization processes.

The mission concept involves two co-planar, counter-orbiting, three-axis-stabilized spacecraft with different eccentricities, altitudes, and propulsion capabilities. The spacecraft will be instrumented with a combination of remote sensing systems (including imaging systems) and ***in-situ*** devices to measure the full complement of neutral atmospheric and ionospheric parameters necessary to attack the above objectives. One of the spacecraft will be in an initial orbit of high eccentricity (~120 x 1000 km) in order to enable direct ***in-situ*** measurements at the lowest altitudes. This spacecraft will be reconfigured into a circular orbit (~400 km) by on-board propulsion at a later time. The second spacecraft will be in a higher-altitude circular orbit (~600 km). The varying angular separation and regular vertical coincidences of the two spacecraft will allow tomographic reconstruction of atmospheric parameters and vertical profiling. In the circular phase, projected for operations in excess of two years, the two co-planar spacecraft will be vertically coincident twice every orbit, allowing for studies of altitude variations of particle distributions, plasma and thermospheric irregularities, and altitude-dependent instability growth rates. At varying locations of vertical coincidences, the mission will explore fluxtube coupling processes, inter-hemispheric responses to dynamic solar, interplanetary and magnetospheric events, conjugacy effects, and simultaneous day/night variability.

5.2.3 The ITM Coupler

For a start near the year 2000, the ITM Panel has defined the "major" ITM Coupler mission for a detailed investigation focused on a comprehensive understanding of the ITM system, its seasonal, solar-cycle, and diurnal variabilities, and its associated spatial and temporal responses to quiet and disturbed conditions. The ITM Coupler will be a comprehensive multi-spacecraft mission. With a measurement and modeling activity designed for simultaneous global-scale diagnostics, it will quantify the chemical, energetic, dynamic, radiative, and electrodynamic coupling terms within the ITM and between the ITM and its neighboring regions. The measurements will cover the densities, composition, energy distributions, and radiative properties of charged and neutral constituents, including their morphologies relative to simultaneously-determined electric fields, currents, winds, and irregularity distributions. The measurements will be global, cover the full spectrum of solar-terrestrial conditions and associated internal and external coupling mechanisms, and encompass quiescent and dynamic conditions carried to the limit of highly irregular and unstable modes.

The ITM Coupler mission will:

- Determine the relative contribution to ITM energy budget from the various energy sources (EUV, UV, cosmic rays, auroral and ring current particles, Joule heating, tides, and gravity waves);

- Determine the relative contributions of the various energy sinks (ionization, excitation, thermal conduction, radiative cooling, etc.) to the ITM energy budget;

- Determine the spectrum of dynamical motions in the mesosphere and lower thermosphere, and determine how the various motions (gravity waves, tides, and impulsive perturbations) are dissipated;

- Determine the global distributions of electric fields and thermospheric winds under quiet and disturbed conditions;

- Determine how energy within the ITM system is transferred and dissipated in transition between large- and small-scale phenomenologies;

- Determine the effect of mesoscale structure on the mean circulation;

- Determine the fundamental processes responsible for eddy diffusion, conduction, and viscosity, and the consequences of these processes;

- Determine how anomalous transport processes affect the flow of momentum and energy into and out of the ionosphere;

- Determine how the dynamical behavior of the neutral atmosphere influences electrodynamic coupling;

- Determine how ionospheric plasma distributions and associated current systems respond to magnetic storms;

- Determine where and how the magnetospheric and atmospheric currents close in the ionosphere;

- Determine the role of the ionosphere in populating the magnetospheric plasma—and determine the source regions and mechanisms for energetic ion outflow;

- Determine the influence of large-scale thermospheric circulation on the composition and energetics of the mesosphere;

- Determine the relative roles of winds, electric fields, and ion chemistry in plasma-layer formations.

These scientific goals impose a requirement for a multi-instrumented, multi-spacecraft configuration that includes ***in-situ*** and remote sensing capabilities. The ***in-situ*** capabilities will provide the highest-resolution measurements of local thermal, suprathermal, and energetic particles, currents, and fields; thermospheric winds; and the cascading processes between large- and small-scale features. Capabilities will include determination of Maxwellian and non-Maxwellian energy distributions, associated anisotropies, and cause-effect roles in momentum and energy transfer within and across ITM boundaries. These measurements will be complemented by remote sensing and imaging detectors. Monochromatic imagers will monitor the exchange of chemical species, wave-momentum stresses, and particle and wave energy in the mesosphere and thermosphere. Time-dependent observations of atmospheric emissions will determine energy-deposition rates from solar radiation and particle precipitation. Remote sensing of major and minor thermospheric constituents will determine the baseline state of the upper atmosphere and monitor possible anthropogenic changes. The unique combination of ***in-situ*** and remote sensing techniques will enable a more detailed understanding of coupling processes and expand the measurement profiles to two and three dimensions.

The measurement criteria and mission objectives require three types of spacecraft orbits: 1) circular, low-altitude (~400 km), and long-lived, to measure global distributions of electric fields, thermospheric winds, upper mesospheric structures, particle and radiation inputs, and dynamic plasma interactions; 2) low-perigee, elliptical (~120 x 4000 km) to penetrate the lower thermospheric and ionospheric domains for long-term ***in-situ*** measurements of localized distributions of winds, electric fields, ion inventories and neutral- and charged-particle layer distributions; and 3) high-altitude, elliptical (~1000 x 8000 km) to provide synoptic large-scale imaging and scan-platform diagnostics of auroral oval dynamics, thermospheric structures, and ionospheric/atmospheric responses to energetic inputs.

The configuration employs a baseline of eight spacecraft to provide the necessary spatial and temporal coverage. Four spacecraft will be designed to operate in low-altitude circular orbits and two each in low- and high-elliptical orbits. The four circular-orbiting spacecraft will be configured to operate at the same altitude—three in different Sun-synchronous planes (4 am/4 pm; noon/midnight; and 8 am/8 pm) and one in a low- to mid-inclination orbit.

The four circularly-orbiting spacecraft would be phased so that the low-inclination orbiter would routinely establish time-coincident points of cross-track coordinate registration with each of the sun-synchronous satellites. Every 90 minutes, there would be six cross-track encounters (three dayside and three nightside), providing "local" synchronized meridional and zonal data sets. Coupling the *in-situ* and remote sensing techniques with coordinated ground-based diagnostics would provide extensive three-dimensional coverage with a systematically-acquired database of UT/LT, latitudinal, longitudinal, solar-cycle and seasonal variations. In the same 90-minute period in which the spacecraft have established the cross-track diagnostics, the three Sun-synchronous spacecraft would also provide synchronized measurements of the convection electric field, currents, precipitating particles and thermospheric winds across the north/south polar regions.

The coordinated multi-spacecraft ITM Coupler mission will be ready for a new start near the year 2000. Technological challenges would be incorporated in instrumentation and spacecraft design, particularly in the area of imaging and altitude profiling. A pre-phase-A definition study was conducted during the ITM/SIS period. That study, supported by the ITM Panel and the Goddard Space Flight Center, analyzed and documented candidate payload configurations, spacecraft systems and subsystems, and orbit scenarios which satisfied the overall diagnostic requirements and provided the cross-track encounters and synchronized data sets described in the mission phase. This mission is the top priority for the ITM discipline. It will provide an important complement to programs in magnetospheric and lower-atmosphere physics, and provide a coherent quantitative perspective on the entire spectrum of solar-terrestrial coupling mechanisms, especially as those coupling mechanisms bear on the naturally-occurring and anthropogenically-controlled influences on the Earth's near-space environment.

5.2.4 Supporting Infrastructure

On their own, the two mission concepts described above do not represent a complete and healthy program for ITM physics. A spectrum of missions, including regular smaller spaceflight opportunities, is essential to provide for quick-response investigations and to provide instrument development opportunities. Many ideas were discussed during the ITM Panel deliberations involving Explorer and Scout-class missions, as well as balloon, rocket, and airplane-borne experiments. Some of the details of these discussions are presented here.

5.2.4.1 SMEX and BEX Explorer-Class Missions

There is a continuing need for Explorer (BEX) and Scout-class (SMEX) missions within the ITM discipline. This is a community that has used Explorer-class missions to great effect. Table 5-1 presents a partial list of some extremely attractive SMEX and BEX mission candidates considered of great importance to the continuing health of the discipline. The Panel strongly supported the need for enhanced ITM activity within the Explorer program.

5.2.4.2 Ground-Based and Suborbital Programs and the Role of Theory and Laboratory Simulations

Rockets and balloons will continue to play an important role in the study of the ITM system. This is particularly true for the mesosphere and lower thermosphere/ionosphere, where coordinated rocket and balloon programs are an effective way to obtain regional *in-situ* data on electric fields, charged and neutral particle composition, velocity distributions, currents, and corresponding electrodynamic processes. Rockets also provide a quick-

Title	Objectives	Comments/Requirements
Tethered Mission to the Lower Thermosphere and Ionosphere	*In-situ* study of vertical and horizontal profiles of thermospheric and ionospheric structures at low altitudes	Pre-Phase A study completed, Multi-payload in a "string of pearls" concept covering the 120–200 km domain
Mesospheric Structure, Dynamics, and Chemistry	Long-term trends in mesospheric structure, Anthropogenic effects	Pre-Phase A study completed, 11-year mission, Sun-synchronous
Time-Dependent Global Electrodynamics	Extremely high temporal and spatial resolution measurements of convection electric fields	Pre-Phase A study completed, Involves large fleet of small, low-cost spacecraft
MELTER	Mesosphere and lower thermosphere waves, dynamics, and chemistry	Delta launch, Phase A study completed
Ionospheric Irregularities	Source, evolution and decay of irregularities; wave vector identification	2 s/c, 250 x 1500km, 1–90° inclination, 1–60° inclination
Active Experiments Satellite (chemical release)	Field-line tracking, Field-aligned potentials and particle acceleration mechanisms	Polar 2000–1000 km
WISP and Topside Sounder	Wave injection efficiency, Wave-particle interactions	Polar, elliptical
Mesospheric Dynamics	Electrodynamics, chemistry, and the role of aerosols in the mesosphere	Sounding rockets and balloons
Tropospheric-ITM Transients	Effects of lightning on ITM wave structure	Polar, elliptical
Ozone Trend Explorer	Long-term trends in mesospheric O_3	Sun synchronous
CHAMPION	Coupling of Heliospheric, Atmospheric, and Magnetospheric Processes in the Ionosphere	SMEX mission 450 km circular 75° inclination Pre-Phase A study completed
GITIM	Imaging of dynamics in the ITM system	900 km, Sun synchronous
New Imaging Techniques for Electric Fields	Radar imaging of mesoscale electric field patterns	Polar, topside ionosphere
Gas Kinetics Explorer	Transition region between collisionless and collision dominated regions	Inclination TBD; elliptical with low perigee
Solium LIDAR from Orbit	Mesospheric structure	STS system
Tidal Explorer	Lower thermospheric tides	SMEX mission

Table 5-1 Partial unprioritized listing of candidate Explorer-class and smaller missions

response experiment platform for event-focused investigations, including, for example, polar cap absorption events, electrojet irregularities, mesospheric ion chemistry during a relativistic-electron precipitation event, and active experiments using particle beams, wave injection, or chemical releases to simulate relevant plasma processes in the solar-terrestrial system.

Ground-based diagnostics of the ITM are important in their own right for long-duration synoptic information on local phenomenologies, and in providing corroborating databases in support of rocket, balloon, and satellite investigations. Radars (both incoherent- and coherent-scatter types), ionosondes, and various optical instruments all have complementary roles to play.

It is also important to maintain an active laboratory program that supports instrumentation development, simulations of space plasma processes, and studies of relevant collision and reaction cross-sections. Such efforts not only provide an important foundation for technology developments of future spaceborne diagnostic systems, but also allow detailed parameter studies (with re-validation and cross-correlation capabilities and unlimited spatial and temporal resolution) of mechanisms active in various components of the ITM system. Another critical component of the infrastructural support necessary for the success of an ITM mission involves theoretical modeling and numerical simulations. One-, two-, and three-dimensional models and codes already exist with varying degrees of sophistication in their representations of micro-, meso-, and planetary-scale processes. These models will play an important role in organizing and understanding the coupling processes in the ITM system; and the models and codes will themselves be updated and improved through detailed comparison with the new data sets provided by the TIMED and ITM Coupler missions.

5.2.5 The Space Exploration Initiative and the Mars Aeronomy Observer Missions

The ITM Panel endorses the scientific objectives of the Mars Aeronomy Observer Mission (MAO) and feels that this mission could and should be supported naturally within the context of the SEI program.

The upper atmospheres and ionospheres of Earth and Mars are controlled by the same physical processes (e.g., photoionization, dissociation, and excitation), but with quite different relative importances that are determined by variations with solar distance, atmospheric composition, gravitational-field strengths, and magnetic properties of the planet. Existing theoretical models of our ITM system are believed to contain all of the relevant processes, but these models have been tuned to the conditions at Earth. Many parameters of the Earth's ITM system are too poorly known, however, to avoid the need for ad-hoc assumptions about the remaining free parameters in the theory, thus rendering more uncertain the identification of the relevant processes. The application of these Earth-driven models to the ITM system of Mars will provide a severe test of the models and consequent improvements in their ability to describe our own ITM system. This approach has been highly successful in comparative planetary studies involving the ITM system of Venus, and we can expect additional improvements in the models when Mars measurements are available.

The basic MAO scientific objectives and strawman mission payload have been described in a detailed Phase-A study (NASA/JPL Tech. Memo 89202). Briefly, they are as follows:

- To explore for the first time the thermosphere, ionosphere, and mesosphere of Mars and the effects of the interaction of the solar wind with these regions;

- To investigate the photochemistry, heat budget, and dynamics of the Martian upper atmosphere in the context of our understanding of such processes from similar missions already conducted at Earth and Venus;

- To examine the effects on the upper atmosphere of tropospherically-generated atmospheric waves and dust storms;

- To test current aeronomic theory against the reality of a different atmosphere which is subject to the same physical processes, but in different combinations, and with different results. (Comparative planetary study using our knowledge of the upper atmospheres of Earth, Venus, Mars, Titan, etc.).

The ITM Panel endorses MAO as a key element of the SEI program. Knowledge of the upper atmospheric density and its variability is crucial to the use of aerocapture to achieve Mars orbit with large payloads at low cost. MAO measurements will be particularly valuable in identifying Mars locations or conditions which lead to greatest risk for aerocapture.

5.3 Discussion

The ambitious ITM Program has been developed to be ***scientifically focused and achievable.*** There are scientific, societal and practical benefits that would accrue from such a program and some of the more significant ones are summarized below.

5.3.1.1 Anthropogenic Changes in the Mesosphere: A Harbinger of Global Change?

The mesosphere, lying between about 50 and 95 km altitude, is an atmospheric region with complex dynamics and photochemistry that is highly susceptible to changes in solar UV radiation. Furthermore, the increasing levels of methane and CO_2 in the mesosphere undoubtedly will influence the delicate chemical and dynamical balances known to exist there. The mesosphere is, therefore, an important test bed for studies of global change because of its high susceptibility to changes induced by varying abundances of trace constituents, such as CO_2 and methane. There is an urgent need to establish the current mean state of the mesosphere so that we can investigate future anthropogenically-caused perturbations to that state.

5.3.1.2 Satellite Drag and Shuttle Re-Entry

The drag on space vehicles is directly proportional to the total density encountered along the orbital path. Previous studies have shown that the density structure of the mesosphere and thermosphere is highly structured in space and time, with changes in density of up to an order of magnitude or more occurring in association with geomagnetic storms or solar-cycle variations. These density changes are driven by a complicated mixture of radiative and dynamic forcings. Previous and sometimes painful experience has also shown the importance of a detailed understanding of these changes for mission-planning purposes and budgeting. Important satellites have re-entered well ahead of schedule; and complex systems, such as the Hubble Space Telescope, need expensive periodic reboosting. Clearly, we need to understand how, where and why density variations occur in the mesosphere and thermosphere in order to improve NASA's ability to model and predict satellite lifetimes and to design re-entry procedures.

5.3.1.3 Plasma Instabilities, Ionospheric Irregularities, and Effects on Communications, Surveillance, and Radar Imaging Systems

Plasma-instability processes are ubiquitous in the Earth's ionosphere, creating plasma-density irregularities with scale-size distributions covering structures from tens of kilometers to fractions of a meter. These distributions are related to energy-transfer processes that involve poorly understood and improperly diagnosed instability mechanisms; and they represent source regions for major perturbations of electromagnetic wave propagation systems operating over the frequency range from HF to EHF. ITM studies of these cascading processes will result in a definitive understanding of the hierarchy of active plasma-instability processes and a formalism and predictive scheme vital for the development of future electromagnetic-wave-system architectures.

5.3.1.4 Aerobraking in Planetary Atmospheres

Aerobraking in the Earth's atmosphere is an issue for the National Aerospace Plane (NASP), STS re-entry, the AOTV, and other programs. *In* *order to perform engineering designs properly, improved models of middle and upper atmosphere density structures and variability are needed.* Also, the human safety considerations for a manned mission to Mars imply a requirement for aerobraking prior to landing on the Martian surface. For aerobraking to be safe on Earth or on Mars, it is critical to have a reliable description of the mean state and the variability of the density structure in the mesosphere and lower thermosphere.

5.3.1.5 Predictability of Ionospheric, Thermospheric, and Mesospheric Processes

Predictability of ITM processes represents a long-term goal for the discipline. The ability to predict correctly climatology and weather of a complicated system, such as the upper atmosphere and ionosphere, requires a complete knowledge and understanding of the important physics processes and mechanisms. *A predictive capability for ITM "weather" is not outside the bounds of possibility and should represent a natural end goal for the research program discussed here.*

5.3.2 Closing Comments on the Consensus Scenario and ITM Infrastructural Requirements

It is the view of the ITM Panel that the overall objectives of the Space Physics Division and the guidelines of OSSA and NASA are well satisfied with the current placement of the TIMED and ITM Coupler missions within the consensus scenarios. With the ITM community having been without a spacecraft mission since the era of the Dynamics Explorer program, the expedient start-up of the TIMED mission will not only revitalize the study of important science of the Earth's near-space environment, but it will provide the missing link in the current ISTP and UARS study of solar-terrestrial coupling processes. The TIMED mission will also provide an important exploratory baseline for the follow-on mission of the ITM Coupler. That mission is also well positioned in the scenarios for important cross-disciplinary studies with solar, interplanetary, and magnetospheric physics. Both the TIMED and ITM Coupler missions are viewed as critically important to the study of the ITM system itself and to the understanding of the overall processes involved in the transfer of energy and mass in the Sun-Earth system.

The Panel also made special note of the infrastructural requirements which bear on the overall strength and vitality of a comprehensive, forward-looking program of ITM research. These requirements include vigorous ITM roles in Explorer-class programs, intensified exploitation of rocket and balloon platforms, expanded theoretical and numerical modeling activities, and concerted programs of laboratory-based space-plasma simulations and sensor technology development.

6.0 Magnetospheric Physics

The Magnetospheric Physics Panel proposes a coordinated program of moderate, intermediate, and small missions to address fundamental questions about the Earth's magnetosphere that ISTP will leave unanswered, while at the same time generalizing our understanding of magnetospheres through comparative magnetospheric studies. Two moderate missions (Mercury Orbiter and Grand Tour Cluster) and two intermediate missions (Auroral Cluster and Inner Magnetosphere Imager) are the primary elements of the proposed program. A number of smaller, Explorer-class missions are also proposed.

6.1 Introduction

Almost a non-existent discipline before 1958, magnetospheric physics has grown explosively in the three decades of the space age. We have come from the initial recognition of the existence of the Earth's magnetosphere to a considerable understanding of most of its global properties. As our knowledge of the terrestrial magnetosphere has grown, planetary missions have also given us our first, tantalizingly incomplete glimpses of the magnetospheres of other planets, and it has become possible to situate the study of the Earth's magnetosphere within a broader, comparative context.

Although the scope of our discipline encompasses the magnetospheres of the planets and other solar-system bodies, it is the Earth's magnetosphere that has been the object of the most intense study and that is best understood. From many spacecraft in diverse orbits at different times we have obtained a general picture of the average morphology of the Earth's magnetosphere and its various distinct regions, including the ring current and the radiation belts, the magnetopause, the bow shock, the plasmasphere, the plasma sheet, the polar cap and cusp, as well as various boundary layers. Past spacecraft missions have also demonstrated that the magnetosphere is a very complex and dynamic system, with strong couplings occurring on a wide range of spatial and temporal scales in thin transition and boundary regions, across which stresses are exerted, particles can be transported, and fields can penetrate. These flows of momentum, mass, and energy across the boundaries are mediated by both large- and small-scale processes, including magnetic reconnection, Kelvin-Helmholtz instabilities, wave-particle interactions, and particle drifts. We have learned that the solar wind is the dominant source of energy for the terrestrial magnetosphere but that the ionosphere plays an exceedingly important role in the coupling and transport of that energy through the system. Moreover, the ionosphere is now known to be a significant, at times dominant, source of magnetospheric plasma. Past missions have also provided ample testimony to the rich variety of microscopic collisionless plasma processes that affect the macroscopic dynamics. However, despite great advances in the understanding of individual magnetospheric domains and of many of the processes coupling them, it has not yet been possible to synthesize the whole; it is not known how various magnetospheric domains fit together as parts of an interacting system, coupled to each other as well as to the solar wind and ionosphere.

In contrast to the study of the Earth's magnetosphere, our study of planetary magnetospheres still remains in its exploratory stage. We have had an orbital investigation only of Venus, while brief fly-throughs have been made of all the other planetary magnetospheres except Pluto's. We have determined that planetary ionospheres, satellites, and rings can be the dominant plasma sources within magnetospheres. We have seen cases in which planetary rotation is the dominant source of particle energization, while at Earth it is negligible; and we have observed auroras that may be powered by this rotation and not by substorm phenomena as at Earth. On the other hand, substorms may well occur at many planets, particularly Mercury and Uranus, but the flybys could not confirm their presence or absence.

6.1.1 Scope and Theme

The International Solar Terrestrial Physics (ISTP) Program, Galileo, and Cassini form the centerpiece of our present magnetospheric research efforts and will significantly advance our understanding of the terrestrial and planetary magnetospheres. These missions will, however, leave important questions unanswered, and they will certainly give rise to new ones. The program set forth below for magnetospheric research during the next two decades represents a coherent approach designed to expand and deepen our understanding of the fundamental problems of magnetospheric physics by answering the challenging scientific questions that will not be addressed by ISTP or planetary missions that are at present approved or underway.

In formulating scientific objectives to be pursued during the next two decades and designing the missions best suited to address these objectives, it is useful to think of a magnetosphere and the various regions within it as cellular structures separated by thin transition or boundary regions. The bulk of the mass, energy, and momentum reside in the large-volume cells and constitute the magnetosphere as a macroscopic physical object. However, it is in the transitional regions where the driving physical processes occur, transporting mass, momentum, and energy between cells and simultaneously propagating signals along the boundaries to remote parts of the magnetosphere. The determining physics of a magnetosphere, in other words, happens in the microscopic transition regions, while the response of the magnetosphere as a system is manifested in the macroscopic cells.

This fundamental characterization of the magnetosphere as a macroscopic cellular structure within which smaller-scale plasma cells are embedded suggests that the right exploratory strategy is to use a mix of microscopic and macroscopic techniques, of "microscopes" and "telescopes." The ISTP project is an initial attempt to implement such a strategy with multiple spacecraft and auroral imaging to provide at least a sketchy global perspective and the Cluster satellites to examine sharp gradients. But technological advances now seem to present the possibility of imaging the whole magnetosphere, including some large portion of the tail. If such imaging is indeed possible, then combined with internal magnetosphere measurements by sets of satellite "clusters," it would constitute an order-of-magnitude improvement over the capabilities of ISTP. As in ISTP, our "microscopes" would be clusters of spacecraft with the instrumental resolution in space-time sufficient to resolve the plasma physics of the transition regions, placed in orbits that will maximize their encounters with the domains of interest (regions left unexplored or underexplored by ISTP). Our "telescopes" would be imagers—detectors of UV, EUV, X rays, and energetic neutral atoms—placed in orbits that optimize their views of all the cells (and their boundaries) that make up the extended magnetosphere. The full realization of the potential of this strategy will come with the deployment of clusters of clusters, and multipoint imagers, so that the microphysics and macrophysics of the entire magnetosphere (and its coupling to the ionosphere and interplanetary medium) will be revealed by simultaneous and coordinated observations.

Ultimately, a strategy appropriate for the Earth's magnetosphere will, when suitably modified, be close to ideal for any one of the other magnetospheres we know about. While each mission to another planetary magnetosphere will of necessity have several unique aspects, we will ideally use the imaging and cluster approaches in order to investigate the large and small-scale plasma phenomena that characterize and control each magnetospheric system. What is needed is to go into each magnetosphere, identify its cellular structure, the important boundaries and transition regions, the major plasma sources and sinks, and the processes of momentum and energy transfer that control the magnetospheric environment. The flyby missions conducted to date have provided valuable snapshots of all of the planetary magnetospheres except Pluto's but have given us very little information about their dynamics. The orbiting missions, Pioneer Venus, Galileo, and Cassini, represent the next logical step in identifying how the magnetospheres interact with the solar wind and with their own ionospheres and atmospheres. The further steps might be (1) to conduct an orbital investigation of Mercury, which possesses a small but significant intrinsic magnetic field and a conducting, sodium-emitting surface, and (2) to go into a polar orbit at Jupiter to search for the existence of high-latitude plasma sources and acceleration and to image the Jovian particle environment as we may be able to do at Saturn with Cassini.

6.1.2 Scientific Objectives

The fundamental scientific objectives of magnetospheric research have remained the same throughout the evolution of the field, although they now encompass considerably more complexity and specificity. These objectives are:

- To understand the structure and large-scale dynamics of the Earth's magnetosphere and the magnetospheres of the planets

- To understand the plasma physical processes operating within the various magnetospheres

- To understand the sources of magnetospheric plasmas and the causes of variations in their source strengths

- To understand how mass, momentum, and energy are transmitted from the solar wind into a magnetosphere

- To understand how energy is transported, exchanged, and transformed within magnetospheres

- To understand quantitatively the coupling between magnetospheres and their ionospheres

- To understand magnetospheric current systems and their role in the solar-wind/magnetosphere coupling

- To understand the magnetospheric mechanisms which accelerate particles to high energies, as well as the ultimate fate of those particles

- To understand the range of variability in the structure, processes, and dynamics possible for a wide range of magnetospheres, both planetary and astrophysical

6.1.3 Science Measurements

Progress in magnetospheric physics is predicated upon an adequate supply of two types of data: (1) global or synoptic observations of the entire system, and (2) small-scale-length, high-time-resolution measurements of microscale plasma processes. The former allow the distribution of plasma throughout the magnetosphere to be tracked as a function of time; the latter will make possible the characterization of microphysical processes, which control phenomena such as x-lines, double-layers, slow shocks, and wave-particle interactions. The critical issue for the magnetospheric discipline is determining the optimal mix of macroscopic and microscopic techniques.

6.1.3.1 Macroscopic Techniques

Two techniques are available which together provide a comprehensive view of the magnetosphere: (1) widely spaced multipoint ***in-situ*** measurements and (2) remote imaging using energetic neutral atoms and UV and EUV detectors, as well as radio wave techniques. The multipoint approach utilizes a constellation of spacecraft at various locations within the magnetosphere to build up an image of its global state. This technique has the advantage of using well-developed spacecraft/instrument technology, such as are employed by ISTP, and providing high-resolution measurements at the location of each spacecraft. The main disadvantage of the multipoint technique is that with a small number of spacecraft the granularity of the global measurements is very poor. Furthermore, the image is significantly blurred by dynamical effects.

Remote sensing techniques involving energetic neutral atoms (ENA) generated by charge exchange between exospheric or interplanetary hydrogen atoms and energetic magnetospheric ions have been demonstrated previously and are now under intensive study. The possibility of sensing magnetospheric plasma via resonant scatter of solar EUV lines from singly ionized helium and oxygen atoms has also been known for some time. Technological issues, such as sensitivity, background (S/N), field-of-view, and temporal resolution are still being evaluated, but hold significant promise for extending remote EUV imaging to greater altitudes than is possible for ENA.

In addition to the above two remote-sensing techniques, barium shaped charges producing fluorescent plasma can be used to trace magnetic field lines directly. With the release of barium particles at an altitude of 25,000 km in the nightside magnetosphere, it may be possible to illuminate the magnetic flux tube for a distance of about 100,000 km and for as long as about one hour. Such a flux tube might connect the auroral ionosphere to the ring-current region or the tail plasma sheet.

6.1.3.2 Microscopic Techniques

The aforementioned techniques would provide a macroscopic view of the magnetosphere and the various domains within it, and of the mesoscale and macroscale dynamics of the system. However, we have learned that the various magnetospheric domains are separated by thin transitional or boundary regions in which most of the driving physical processes occur on a microscale, transporting mass, momentum and energy between domains. In order to study these microscale processes, rather closely-spaced arrays or clusters of spacecraft are needed in order to probe the structure and dynamics of the transitional layers on appropriate spatial and temporal scales. These spacecraft clusters represent the "microscopes" that we need to complete the comprehensive view of the magnetosphere that is required.

The choice of an optimum mix among these techniques is determined by the particular aspect of magnetospheric dynamics or structure under investigation. In the mission concepts discussed in this report, multipoint missions are proposed to attack more narrowly focused objectives such as reconnection at the dayside magnetopause, the injection of hot plasma into the nightside magnetosphere during substorms, and auroral electrodynamics. Stereoscopic remote imaging missions will be needed when the coupling of mass and energy between different regions of the magnetosphere are considered. Ultimately, however, both macroscopic and microscopic techniques must be simultaneously employed.

Moderate

- Grand Tour Cluster
- Mercury Orbiter

Intermediate

- Inner Magnetosphere Imager
- Auroral Cluster

Small

- Inner Magnetosphere Imaging Precursor
- Active Field Line Tracing
- Analog Magnetospheric Plasma Laboratory
- Solar Wind/IMF Input Monitor
- Energetic Injection Plasma Laboratory

Table 6-1 Magnetospheric physics proposed programs

6.2 Proposed New Magnetospheric Missions

Future magnetospheric missions that satisfy the defined science objectives are made up of 4 separate and complementary components: (1) global imaging; (2) *in-situ* clustered spacecraft; (3) active experiments; and (4) planetary missions. Missions of all four types are included in the recommended program for magnetospheric physics described below. The proposed Magnetospheric Physics Program consists of two moderate missions, two intermediate missions, and a variety of small missions, as illustrated in Table 6-1. We will discuss each of these proposed missions in the following sections.

6.2.1 Moderate Missions

6.2.1.1 Grand Tour Cluster

The Grand Tour Cluster (GTC) consists of a cluster of 4 maneuverable spacecraft in elliptical orbits with apogees that range from ~ 7 R_E to 200 R_E with variable inclination. When combined with the imaging capabilities of the Inner Magnetosphere Imager (see below), this mission provides:

- A multipoint probe of the magnetopause at both low and high latitudes for investigation of flux transfer events, steady-state merging, impulsive plasma penetration, and other possible processes of energy and momentum transfer

- A detailed probe of magnetotail boundaries and current systems and of their relation to inner magnetosphere/ionosphere boundaries and current systems

- A means of testing the plasmoid model of magnetospheric substorms

- A measure of the way in which major macroscale regions of the magnetosphere interact on a global scale

- A measure of the relation and interplay between local processes and global dynamics

The GTC will use propulsion to achieve a series of different orbits for specific magnetospheric investigations. The three prime phases of the mission will be (1) the equatorial magnetopause and near-Earth plasma sheet phase, (2) the magnetopause/ boundary layer phase, and (3) the distant magnetotail phase. Each of these mission phases is described separately in the following paragraphs.

The *Equatorial Magnetopause and Near-Plasma Sheet Phase* of the GTC mission will focus on the low-latitude region of the dayside magnetopause and the substorm plasma injection region on the night side. The magnetopause is the site of mass, energy, and momentum transfer between the solar wind and the magnetosphere. We are currently faced with a bewildering array of possible steady and transient interaction mechanisms. Each predicts a specific pattern of magnetic-field, electric-field, plasma, and energetic-particle signatures as functions of position on the magnetopause surface. The subsolar or equatorial magnetopause is believed to be the dominant site of solar wind-magnetosphere interaction; prolonged observations are essential in this region. To date there has been no comprehensive survey of processes occurring at very low latitude, and the contemporary data cannot uniquely distinguish among the possible processes nor their relative importance. The inner edge of the plasma sheet and the near-magnetotail is the region where the substorm process may be initiated. In this region, the magnetic field makes the transition from dipole-like to tail-like and substorm plasma injection occurs. Although the region near geosynchronous orbit has been well explored, the region from ~ 7–12 R_E is very much underexplored. This area must be surveyed in order to understand the processes that produce particle injections, the disruption of the cross-tail current, the change in field topology and the mapping of field-aligned currents.

To understand the important physical processes operating both at the magnetopause and in the near-tail, a cluster of four properly instrumented spacecraft is required. Utilizing variable separations between spacecraft, the cluster will make it possible to separate spatial from temporal variations and to determine the spatial morphology of the structures of interest. This phase of the mission will investigate the coupling of magnetospheric domains and, in particular, will focus on domain boundaries and coupling across spatial and temporal regimes.

Some specific objectives of the magnetopause and near-plasma sheet phase of the GTC mission are to:

- Study in detail magnetopause structure and processes (FTE's, pressure pulses, surface waves, impulsive entry, steady-state or enhanced merging)

- Examine solar wind and IMF control of each of these processes

- Resolve space-time ambiguities by lingering in the equatorial magnetopause region with a high-time-resolution, variably-spaced cluster

- Perform a detailed investigation at all local times on the dayside

- Examine the near-tail region with cuts through the transition region from dipolar to tail-like geometry

• Determine the processes involved in substorm particle injection

• Identify the process of current sheet interruption

To address these science objectives, measurements of the following are needed: DC and AC electric and magnetic fields; 3-D ion composition (0 to 50 keV); 3-D electrons (few eV to 50 keV); cold electron density, temperature, and density fluctuations; energetic-ion composition (up to few MeV/nucleon); and energetic electrons (to 1 MeV). An upstream monitor of the solar wind is required. The scientific return will be enhanced if the Inner Magnetosphere Imager is operational during part of this mission.

The *Magnetopause/Boundary Layer Phase* of the GTC mission consists of four polar-orbiting spacecraft intended to explore in depth three important boundary regions of the magnetosphere: the dayside magnetopause (at all latitudes and local times); the high-latitude magnetopause on the night side and the polar cusp; and the region near 10 R_E in the tail, which is the transition region between the near-Earth ring current and the tail plasma sheet. The orbit would initially be a 10 R_E circular polar orbit, with the local time of the orbit plane at about 1500–0300 hrs. At this distance and local time, the spacecraft would spend about 15 hours skimming the dayside magnetopause from the southern to northern cusp every two days, crossing over the pole and then traversing the tail from north to south and returning to the day side. The orbit, virtually inertially stable, would decrease in local time by two hours per month, reaching 0900–2100 MLT after three months. At this point, the dayside apogee would be gradually increased to match the flare of the dawnside magnetopause, becoming a 10 x 15 R_E orbit when it reaches the dawn-dusk meridian. At this time the dawnside portion of the orbit would be skimming the magnetopause while the duskside portion would remain in the low-latitude boundary layer, investigating particle entry mechanisms. Propulsion could also be used to tilt the line of apsides up out of the ecliptic plane, reaching perhaps 35° with an apogee of 30 R_E by one half-year past launch. Now the dayside (perigee) portion would spend about a day skimming the dayside magnetopause from pole to pole (being slightly inside the average magnetopause location in the southern hemisphere and outside of it in the northern hemisphere), and the nightside portion would cross the magnetopause considerably down the tail, once every 5.6 days. In this way, momentum transfer (and supposed northward IMF reconnection) could be investigated in a near-skimming trajectory. The spacecraft would spend about three months traversing the tail in this manner, and then would swing back around to the dayside, investigating the high-latitude bow shock as well.

This mission phase would build upon the results of the equatorial magnetopause/near-plasma sheet phase of the GTC mission. It would break new ground by being the first mission to skim the dayside magnetopause and the turbulent exterior cusp. It would be the first to cross the polar magnetopause at distances tailward of $x \sim -10$ R_E, crossing it at 20 R_E or more. In this way it would be the first to explore the magnetopause cross-section at high latitudes behind the Earth to determine whether the magnetopause continues to flare at high latitudes or its polar cross-section reaches some maximum value and decreases again. It would also address the question of whether the IMF y-component gains access at high latitudes through the merging process or through turbulent diffusion in the equatorial plane. Dayside magnetopause skimming orbits will also make it possible to follow the development of plasma which is injected by FTE's, spatially and/or temporally varying dayside merging, or quasi-diffusive processes.

In the near-tail, the mission can monitor the fate of the plasma mantle to determine whether it eventually reaches the tail neutral sheet and returns as the plasma sheet or whether its supersonic flow never returns. In addition, the mission can trace the fate of ionospheric plasma fountains emitted from the dayside cusp and nightside auroral zone, testing where they convect back to the neutral sheet and providing quantitative tests of the relative importance of mantle plasma versus low-latitude boundary layer and ionospheric plasma in supplying the plasma sheet.

For substorm processes, the magnetopause/boundary layer mission phase will provide an out-of-ecliptic monitor to check the size and motion of plasmoids. It can also, for the first time, allow measurements of the vertical dimension and field strength in the lobes to measure total magnetic flux changes during the growth and expansion phases of substorms.

The polar magnetosheath will also be skimmed for part of this phase of the mission. At this part of the trajectory, one can monitor solar-wind deceleration by current dynamo processes, and perhaps watch bursts of magnetospheric plasma, which will be most easily observed in the magnetosheath just outside the magnetopause. The cluster will spend about 1 day in its 5.6-day orbit out in that region, being engulfed periodically by the magnetopause as it "breathes" and/or flaps.

The *Distant Magnetotail Phase* of the GTC mission will provide *in-situ* magnetotail observations that allow three-dimensional determination of boundaries and current systems throughout the magnetotail. The magnetotail cluster configuration will separate spatial and temporal effects using a variable satellite spacing (from a fraction of an R_E to ~ 10 R_E). One of the prime scientific objectives of the distant magnetotail phase of the GTC will be a test of the plasmoid model of magnetospheric substorms. In this model, proposed by E. W. Hones, Jr., an x-line is formed by reconnection in the near tail at substorm onset. A closed magnetic island or plasmoid is formed and ejected rapidly down the tail. Although the Geotail mission will surely obtain much new information on the phenomena, proper investigation of the proposed moving plasmoids will require a multispacecraft approach, by which spatial and temporal effects can be separated. As with Geotail, the distant magnetotail phase of the GTC will use double lunar swingby trajectories to remain in the magnetotail for long periods of time with excursions out to distances of 200 R_E.

The GTC mission will represent a major advance in our goal of understanding both the global behavior of the magnetosphere and the role of local processes in determining the observed global features. It builds upon and is a natural extension of the ISTP Program, which will study the large-scale mass, momentum, and energy flow through the magnetospheric system, along with turbulent processes in those regions sampled by the ESA Cluster mission. The ISTP data will provide a basis on which to interpret and test the GTC results concerning global dynamics and their relation to local processes.

6.2.1.2 Mercury Orbiter

Mariner 10's encounter with Mercury revealed an Earth-like magnetosphere in miniature, with dynamical processes occurring on time scales of minutes compared with time scales of hours and days at the Earth. Scientifically, Mercury presents us with a unique laboratory for making a self-contained magnetospheric study of plasma convection and particle acceleration in a setting where the effects of planetary rotation are suppressed and the boundary conditions—e.g., a conducting surface and very little atmosphere—are radically different from those prevailing in the Earth's magnetosphere. The primary magnetospheric physics objectives for the Mercury mission are (1) to map in three dimensions the magnetic structure and plasma environment of the planet's "miniature" magnetosphere; (2) to determine the principal processes taking place during magnetospheric substorms with an emphasis on differences from terrestrial substorms due to Mercury's lack of an ionosphere; (3) to assess the role of interplanetary conditions in determining the rate at which Mercury's magnetosphere draws energy from the solar wind and the manner in which it is later dissipated; and (4) to exploit Mercury's relative lack of internal plasma sources to measure quantitatively the transfer rate of solar-wind plasma into the magnetosphere.

Within the past few years it has become apparent that a moderate-cost mission to Mercury can provide the particles-and-fields measurements and planetological observations necessary to yield major advances in our understanding of Mercury and its magnetosphere. A Mercury Orbiter Science Working Team (MeO SWT), appointed in 1988 under the auspices of the Space Physics (SS) and Planetary Exploration (SL) Divisions of NASA Headquarters, conducted three workshops in 1988–

89 and was supported by spacecraft engineering and mission design studies at the Jet Propulsion Laboratory. The findings of the engineering team indicate that a pair of spin-stabilized spacecraft carrying comprehensive particles-and-fields experiments and some planetology instruments in highly elliptical orbits can survive and function in Mercury orbit without costly Sun shields and active cooling systems. The MeO/SWT identified a ten-instrument strawman payload to meet the science objectives stated above: magnetometer, electric-field analyzer, plasma wave analyzer, energetic-particle detector, fast-plasma analyzer, ion-composition analyzer, solar-wind plasma analyzer, solar neutron detector, line-scan imager, and gamma/X-ray spectrometer. All of these instruments are based on mature technologies.

The single-launch-vehicle, dual-spacecraft baseline contained in the JPL mission design meets the fundamental magnetospheric science requirements for simultaneous multipoint measurements and provides critical redundancy in the event of spacecraft failure. The coordinated orbit scenarios for the two spacecraft will provide unique particles-and-fields measurements, which are unobtainable elsewhere due to the constraints of orbital mechanics and to the large dimensions of other magnetospheres relative to their planetary bodies. In conjunction with the Earth-orbiting GGS and CLUSTER missions to be flown in the 1990's, the Mercury Orbiter mission will provide the essential data necessary to formulate the next generation of theories and models for terrestrial-type magnetospheric structure and dynamics. This mission will also return critical measurements necessary for the understanding not just of the surface history and internal structure of Mercury, but of the formation and chemical differentiation of the solar system as a whole.

6.2.2 Proposed New Magnetospheric Intermediate Missions

6.2.2.1 Inner Magnetosphere Imager (IMI)

A dramatic advance in our understanding of the global magnetosphere and its dynamics can be obtained through the use of recently developed techniques of imaging the charged particle populations of the magnetosphere. The Inner Magnetosphere Imager will apply these techniques to provide:

- Images of the global ring current and its dynamics
- Images of the plasmasphere and its dynamics
- Images of the inner edges (< 15 R_E) of the plasma sheet and its dynamics
- Images of the auroral regions and their dynamics
- Global mapping from low altitude to the equatorial regions
- A measure of the global interactions among the macroscale regions listed above
- Global images of substorm injections and a measure of the injection boundary
- A measure of the magnetic field/electric field configuration within ~ 15 R_E

The IMI mission will incorporate energetic neutral-atom and photon imaging techniques to obtain global images of various magnetospheric regions. Instrumentation that has already been developed includes UV and visible auroral imaging, energetic neutral atom cameras, and EUV plasmasphere imaging using 30.4 nm He^+ resonantly scattered radiation. The IMI will be placed in a high-inclination, elliptical orbit (apogee altitude in the 5–20 R_E range).

Results from the IMI will provide an entirely new perspective of the magnetosphere on a global basis and, if combined with the GTC and Auroral Cluster missions, will allow an initial assessment of how local processes determine the global dynamics of the system. Such perspectives have not been available in the past and will mark the first time that an astrophysical plasma system can be observed and studied on both global and local scales. The science return of the IMI mission will clearly be strongly enhanced if the Grand Tour Cluster mission and the Auroral Cluster mission are operational during the same time period.

6.2.2.2 Auroral Cluster

The auroral acceleration region is one of the key regions of energy transformation in the magnetosphere. It is the primary region through which energy stored in the outer magnetosphere is coupled to the ionosphere. There are many fundamental, but not well understood, micro- and mesoscale plasma processes involved in this coupling. This region has been explored during the past two decades by several spacecraft including S3-3, DE, and VIKING. These missions established the macro-parameters of this system and have identified the importance of the microscale physics involved, stimulating significant theoretical and modeling activity. However, the single- or dual-point measurements have been inadequate to separate spatial and temporal effects or to uniquely define both the wave frequency and wavelength.

The set of four auroral cluster spacecraft will have the capability to separate temporal and spatial variations, with interspacecraft spacings varying from a few hundred meters to 100 km. The four spacecraft will be identically instrumented to measure electric fields (DC–1MHz), magnetic fields (DC–10 KHz), 3-D electrons (~1 eV–30 keV), 3-D ions with composition (~10 eV–30 keV), and wave-particle correlations. The major technical challenges are the desired 1% knowledge of interspacecraft positions over the full range of separations and the 0.01° relative attitude determination knowledge.

The cluster of spacecraft would be launched into a 1000 km by 12,000 km polar orbit and would initially be in a closely spaced configuration. The cluster would operate throughout the auroral zone but store data at a relatively low rate until the desired event signature was identified by one spacecraft. This would trigger very high-rate (~10 MHz) data capture from all spacecraft for a fixed period surrounding the triggering event (similar to the FAST mission). The effects of dipole wobble and orbit precession would permit an altitude scan of the critical region of auroral acceleration mapped out by previous missions. A two-year mission would suffice to cover all local times and relevant altitudes. This mission would benefit from a continuous solar wind monitor upstream from Earth and from fine-scale auroral imaging from one of the spacecraft. It would also benefit greatly from concurrent operations with the IMI mission described above.

6.2.3 Proposed New Magnetospheric Small Missions

A remarkably broad range of scientific objectives could be served by a steady sequence of Explorers and smaller Explorer-class spacecraft. Indeed, virtually every aspect of magnetospheric research—auroral studies, boundary exploration, particle acceleration, etc.—would profit from focused research with small missions. In addition, Explorer missions would serve as platforms on which to test technologies and concepts that feed into our moderate and major missions. The Magnetospheric Physics Panel thus recommends that a separate Explorer-class line for space physics missions be established as soon as possible to meet this critical, unmet need. The highest priority for a magnetospheric-physics small Explorer mission should be given to the ENA imaging of the ring current and EUV imaging of plasmaspheric helium ions along with auroral imaging. These technologies are ready for a proof-of-concept mission as a precursor to the IMI mission. Small missions were also proposed, and these are discussed below.

6.2.3.1 Active Field Line Tracing

An understanding of the way in which the various regions of the magnetosphere and the ionosphere are connected by the geomagnetic field is essential to our understanding of the physical processes in the magnetosphere. Unfortunately, all past efforts to understand the geometry of magnetic field lines within the magnetosphere have been limited in their spatial coverage and thus have not been decisive. To provide such understanding, a number of tracing techniques have been developed or proposed: chemical tracers, electron accelerators, and positrons. For tracing over large distances, the barium shaped-charge technique appears very promising. A barium shaped charge will create a highly directed neutral beam, which will ionize when exposed to sunlight; the resulting ions will subsequently follow the ambient magnetic field. Since barium ions have resonance lines in the visible portion of the EUV spectrum, the ions can be observed optically. In a dual release, with charges currently used in rocket-based auroral research, but released at high altitude and in opposite directions, up to 100,000 km of magnetic field lines can be illuminated. This distance is sufficient to illuminate an auroral magnetic flux tube from the ionosphere to past its equatorial crossing. It is possible that larger charges will make it possible to trace field lines even farther.

An essential goal of this mission is to increase our understanding of the magnetic configuration of the magnetosphere and how it changes in response to the solar wind and to auroral activity. Therefore, a number of tracing experiments will be carried out under different conditions. Although the barium shaped-charge technique is flight-proven, it has only been used in experiments carried out from rockets in the near-Earth magnetosphere. The estimated 100,000 km tracing possible with releases at higher altitude is based on the rocket experiments. For tracing field lines in the more distant magnetosphere the release must be made at higher altitudes where the magnetic field strength is much smaller. This may affect the distance over which we can trace. Before engaging in a large program with many tracing releases, it is prudent to have a number of test releases for proof of concept. It is also strongly urged that other field-line tracer techniques be studied and that funding be made available for such studies.

6.2.3.2 Analog Magnetospheric Plasma Laboratory

The Analog Magnetospheric Plasma Laboratory (AMPL) provides an experimental laboratory for comparative magnetospheric physics studies in conjunction with the Astromag cosmic ray facility. It falls into the category of an active experiment, since an anthropogenic disturbance of the natural environment is exploited for these studies. It will (1) test the space physics theory of fundamental processes under new conditions, (2) add a new member to the set of magnetospheres accessible to study, and (3) provide a reproducible experimental system which may be imaged, freely sampled, and altered or perturbed in a deliberate and controlled way. A deployable, maneuverable plasma diagnostic probe is used to study the interaction between Astromag and the ambient ionosphere. Various embellishments of the basic concept may be developed as experience is gained. Preliminary studies should include theoretical predictions of Astromag's behavior, and a proof of concept by study of the orbital decay and optical emission of a permanent magnet placed in low earth orbit by a Scout class vehicle.

6.2.3.3 Solar Wind/IMF Input Monitor

Magnetospheric physics has matured to such a point that there is now little doubt that the solar wind is the primary energy and momentum input that drives and controls magnetospheric processes. Thus nearly continuous monitoring of the solar wind and interplanetary magnetic field (IMF) immediately upstream of the Earth is a requirement of essentially all future magnetospheric missions. The ideal monitoring location is from a double lunar swing-by orbit similar to that of the Wind mission. This avoids the problems of aberration which can occur from L1. A simple Explorer spacecraft providing basic solar wind plasma and IMF measurements would replace the Wind spacecraft after it is no longer operable.

6.2.3.4 Energetic Injection Plasma Laboratory (EIPL)

Operation of an injection payload comprising both energetic particle accelerators and intense wave transmitters will enable plasma physics studies and remote sensing of ambient plasma structures, including (1) particle beam-plasma interactions and beam echoes from auroral potential structures, (2) wave-particle interactions of emitted waves across the VLF frequency spectrum, and (3) remote sensing of plasma structures by wave echoes. A deployable, maneuverable plasma diagnostic probe will be used to study the interaction between injected beams or waves and the ambient ionosphere. Various embellishments of the basic concept may be developed as experience is gained in the operation of the injectors. The heritage of this type of experiment consists of several sounding rocket and shuttle payload projects: notably seven Echo experiments, the E-parallel-B rocket, the SEPAC investigation on Spacelab 1 and Atlas, and the FPEG/VCAP experiment on STS 3 and Spacelab 2, which made use of the Plasma Diagnostics Package.

6.2.4 Space Exploration Initiative

If the Space Exploration Initiative (SEI) proceeds as expected, it could provide a significantly enhanced capability for magnetospheric studies. The Moon could be used as a base for large imaging instruments and for remote probing of the Earth's magnetosphere with radio waves. The numerous planned missions to Mars, beginning with the Mars Aeronomy Observer (MAO), could provide opportunities for the detailed study of the Mars plasma environment.

The program discussed herein might, therefore, have the potential of being expanded to include the following experimental capabilities:

- A lunar-based imaging observatory employing EUV, ENA, and radio-wave imaging for macroscopic studies of the Earth's magnetosphere. This capability would greatly enhance the scientific return of the Grand Tour Cluster mission.

- A "lunar magnetosounder" for remote mapping of the Earth's downstream magnetopause, boundary layers, and downstream plasmoids from the lunar base. This facility would add significantly to the science achievable with the distant magnetotail phase of the Grand Tour Cluster mission.

- *In-situ* studies of the interaction of lunar magcons with the solar wind and magnetotail plasmas.

- *In-situ* and remote sensing of the plasma and magnetic-field environment within the Mars/Phobos system.

6.2.5 Theory and Modeling

Future missions will provide an unprecedented data base concerning the dynamics of a wide range of global, mesoscale and microphysical magnetospheric phenomena. A new generation of models must play a dual role in this new phase of exploring and understanding our space environment. These models will provide guidance during the design phases of the missions, and then they will synthesize the new knowledge gained by global imagers and clusters of spacecraft. The major challenges the new models must meet include:

- Integration of microphysical processes into macroscopic transport models. For instance, anomalous processes due to waves excited by wave-particle interaction must be incorporated into macroscopic transport coefficients.

- Incorporation of the cellular structure of the magnetosphere into a global model. This problem is especially complex because of the wide range of cell scale sizes. For example, the permeability of the largest scale cell boundary, the magnetopause, needs to be understood.

- A more accurate treatment of boundary conditions. Of particular importance is the manner in which the ionosphere acts both as a major plasma source and electrodynamic boundary.

- Incorporation of the fact that most of the magnetospheric plasma is a collisionless magnetized multispecies medium, which cannot always be described by classical MHD treatments. A typical example is the need to use complicated non-Maxwellian distributions which are often observed by satellites but not described by MHD equations.

- Inclusion of neutral atmospheric effects in global magnetospheric models. This requires a connection to global thermospheric circulation models, which in turn must be properly linked to the lower atmosphere.

- Incorporation of appropriate data on particles and waves for study of microscopic processes with particle simulations.

6.3 Discussion

The program set forth above seeks to advance our understanding of magnetospheric physics by addressing questions that ISTP, Galileo, and Cassini will not answer.

The proposed missions to study the terrestrial magnetosphere will build upon and expand the ISTP strategy of using a combination of imagers and multispacecraft clusters to develop a global picture of the Earth's magnetosphere as a dynamic system of interacting plasma domains and processes. Imagers will provide a macroscopic view of the dynamics and morphology of the magnetosphere, while clusters will probe the transition regions and investigate the structures and microscale processes occurring there. A prominent role is assigned to small, Explorer-class missions, which are relatively inexpensive and require only modest lead-times and which can be used effectively to investigate many magnetospheric phenomena.

Also proposed is a moderate, dual-spacecraft mission to Mercury. Interesting in its own right, Mercury's miniature, Earth-like magnetosphere will offer a unique laboratory for comparative magnetospheric studies that may help illuminate processes, such as substorms, that occur in the Earth's magnetosphere. Data from both the terrestrial missions and from the Mercury mission will be essential in formulating the next generation of theories and models for terrestrial-type magnetospheric structure and dynamics.

Finally, the Panel proposes an enhanced theory and modeling effort to complement the recommended observational program. Theory and modeling will have the dual function of providing guidance during the mission design phases and of synthesizing the unprecedented amount of data to be gathered during the missions.

7.0 Solar Physics

The Solar Physics Program planned for 1995 to 2010 contains three primary elements, the High-Energy Solar Physics (HESP) mission, the Solar Probe and Solar Probe Companion, and the Global Solar Mission. HESP is a payload containing an instrument capable of obtaining hard X-ray and gamma-ray images with arc-second resolution over a wide energy range. The Solar Probe Companion is an Earth-orbiting spacecraft designed to acquire coronal images and spectroscopic measurements in conjunction with the Solar Probe, a heliospheric mission designed to measure the solar wind via ***in-situ*** techniques as close as 4 solar radii from the Sun. The Global Solar Mission (GSM) uses several spacecraft to obtain a global view of solar magnetic activity and its influence on the solar system. The GSM mission consists of a Solar Polar Orbiter plus one or more spacecraft in the ecliptic. The GSM spacecraft contain optical instruments for studying the Sun via remote sensing techniques and plasma instruments for monitoring the solar wind via ***in-situ*** techniques. Remote sensing optical solar instruments also may be flown in conjunction with other future missions, such as the Mercury Orbiter.

7.1 Introduction

During the coming decades solar research will explore the limits of what can be observed. At one extreme, beginning with OSL, we expect to explore small physical scales where fundamental solar processes occur. At the other extreme, the Sun can only be understood from a global viewpoint; i.e., when considered and observed at a wide range of spatial, temporal, and spectral scales from multiple locations for a determination of structure in three dimensions. Such investigations will use both time series (which have a length of a considerable fraction of the magnetic activity cycle period), and simultaneous viewing of the solar surface.

7.1.1 *Major Themes in Solar Physics*

(i) Identification of the variable nature of the Sun as key in the modulation of the volume of the solar system and the heliosphere.

(ii) Investigation of the short-term variations associated with the evolution of the magnetic activity cycle. Flares, active regions, coronal holes and their associated high-speed wind structures are all shorter-term consequences of the activity cycle, and directly influence the solar neighborhood.

(iii) Investigation of the magnitude and significance of long period solar variability and its influence on various component elements of the solar system and heliosphere. These elements range from the changes which are observed over fractions of a day to those which occur over the range of the magnetic activity cycle.

7.1.2 *Solar Physics Scientific Objectives*

Interior of the Sun. What is the nature of that portion of the Sun which lies below the photosphere? What are the dominant structures and physical processes of the interior, and how do these evolve over the time scales of interest?

Generation of the Magnetic Activity Cycle. What are the physical processes which determine the generation of a magnetic variation in the star? Of what significance is this variation in the modulation of other objects and structures in the solar system?

Energy Storage and Release. How is non-potential magnetic energy stored in the Sun, and how is this magnetic energy converted into other kinetic and thermal forms of energy? How are the energetic particles accelerated to high velocities as the active regions evolve and change?

Solar Activity. What are the physical processes which govern the nature of the plasma structures found in the solar atmosphere in active regions? How are dynamic processes initiated and maintained in the upper layers of the Sun and out into the heliosphere?

Solar Wind and Solar Interaction. What physical mechanisms couple the variability of the Sun to the other elements of the solar system, such elements as the magnetospheres and atmospheres of planets, the modul[illegible] the structure of the plasma flowing away from the Sun in the form of solar wind?

7.1.3 Solar Physics Measurements

These scientific themes and objectives require a large variety of solar measurements. They may be grouped into three broad categories: (1) simultaneous measurements of the Sun from new vantage points, including the solar poles, multiple azimuths in the ecliptic, and regions near the Sun; (2) the quest for higher spatial resolution in all temperature regimes of the solar atmosphere; (3) the long-term measurement of solar radiative and particle outputs which affects plasma and atmospheric processes throughout the solar system.

7.1.3.1 Supporting Research and Technology

The quality and quantity of science from future solar missions such as Solar-A, SOHO, and OSL depends on the vitality of the solar science community. Observational advances require development of new instrumental and observational techniques which exploit both existing and state-of-the-art technology. Because of these factors, we recommend a major augmentation to the funding for Solar Suborbital Programs (including establishment of a Solar Balloon Program) and for advanced technology development. We also recommend significantly increasing the level of support for the Solar Research and Analysis Program, and for the NASA Solar-Terrestrial Theory Program (STTP).

7.2 Proposed New Solar Physics Missions

7.2.1 Proposed New Large Solar Physics Missions

7.2.1.1 Global Solar Mission (GSM)

Overview. Simultaneous remote sensing and *in-situ* measurements from multiple vantage points (over the poles and in the ecliptic) using familiar techniques will provide fundamental new data for understanding the solar interior, the solar atmosphere, the solar wind, and the solar magnetic activity cycle.

Thematic Rationale. The Solar Global Mission addresses all three themes given earlier: identification of the variable nature of the Sun, investigation of short-term variations associated with the evolution of the magnetic activity cycle, and investigation of the magnitude and significance of long-period solar variability and its influence on the heliosphere.

Scientific Rationale. Measurements using familiar techniques from new vantage points will provide fundamental new data on the structure of the quiet and magnetic Sun and the activity cycle. Measurements include coronal morphology; UV/EUV/WL disk and coronal spectra/spectroheliograms for temperatures, densities, flow velocities, and chemical abundances; EUV/soft X-ray imagery, showing magnetic-loop structure in the low corona and coronal holes; vector magnetic fields and Doppler velocities in the low chromosphere and photosphere; full-disk irradiance and velocity for helioseismology and luminosity variability studies; and *in-situ* particles-and-fields measurements and zodiacal light photometry for following solar-wind plasma into the heliosphere.

The polar view of the Sun will allow accurate measurements of the polar magnetic field, differential rotation profile, and meridional flow free from the extreme projection effect of viewing from Earth. The downward view of coronal streamers and mass ejections will show their acceleration and time evolution faithfully for the first time. It will be possible to observe the development and decay of active regions without interruption by the Earth's rotation. Helioseismological probing of the interior will be free from the rotational splitting of the low order modes.

Imaging of a portion of the solar surface or corona from multiple aspect angles can free our observations from both projection effects and line-of-sight averaging. Using two or more views from polar and ecliptic spacecraft, X-ray coronal images and longitudinal magnetic and velocity maps can be converted to full vector measurements in the photosphere and corona. With a full network of ecliptic spacecraft at 1 AU, we can combine these observations to measure the detailed evolution of coronal field connectivity and energy content during the life-cycles of active regions. The three-dimensional geometry of coronal structures can be reconstructed from multiple projections. The low-order global oscillations can be measured without the ambiguity caused by seeing only one solar hemisphere.

In summary, the scientific objectives are:

- Observe the entire Sun from different vantage points simultaneously, to study global magnetic, thermal, rotation, circulation, and oscillation properties never observable before.

- Measure the solar wind *in situ* from different vantage points, including high latitudes, while remote sensing instruments observe the corresponding solar sources of the wind.

- Combine these fundamental new observations with a mission-oriented theoretical program, to understand the origin of the solar magnetic cycle.

- Obtain stereoscopic views of solar structures and events, revealing their true three-dimensional geometry for the first time.

Solar Polar Orbiter

Scientific Goals:

- Measure the polar magnetic field accurately during the time of polar field reversal near the peak of cycle 24.

- Measure the high-latitude differential rotation profile.

- Detect the hypothesized meridional flow by both Doppler and tracer techniques.

- Investigate for pole-equator temperature differences.

- Observe coronal streamers continuously in time and from above, with constant viewing geometry, to deduce the acceleration profile from the spiral shape.

- Observe active regions continuously with constant viewing geometry.

- Observe coronal mass ejections aimed toward the Earth to correlate the coronal instability with evolution of structures on the disk.

- Measure the solar wind *in situ* as a function of solar latitude.

- Observe the solar wind from above, throughout the entire inner solar system, with a Helios-type photometer.

- Perform radio-science experiments on gravity, the solar wind, and the corona during occultations.

- Measure p-modes free of rotational splitting from the pole.

Baseline solar instruments: UV/WL coronagraph, EUV/X-ray imager, longitudinal magnetograph/dopplergraph, low-resolution helioseismometer, radiometer, solar-wind photometer, particles-and-fields experiments.

Ecliptic Stereoscopic Spacecraft (2 to 4)

Scientific goals:

- Determine three-dimensional geometry of specific coronal structures and events including CME's by reconstruction from multiple projections.

- Observe magnetic topology of coronal magnetic fields from multiple projections seen in soft X rays.

- Observe vector magnetic field in the photosphere from longitudinal fields with multiple lines of sight.

• Combine these two observations to study the detailed evolution of coronal-field connectivity and energy content during the entire life cycles of active regions.

• Measure low order global p-modes free from the ambiguity introduced by observing less than half the solar surface.

• Measure solar-cycle effects on convection zone via helioseismology.

• Search for g-modes by measuring the vector velocity in the photosphere, allowing cleaner suppression of solar noise sources from the predominantly horizontal velocities of the modes.

• Measure solar wind *in situ* from different vantage points, while remote sensing instruments observe corresponding sources of the wind.

• Measure global solar constant by integrating over multiple lines-of-sight.

• Conduct definitive studies of periodicities of solar activity, such as active longitudes, sunspot "nests," and the 155-day flare periodicity.

Baseline solar instruments: UV/WL coronagraph, EUV/X-ray imager, longitudinal magnetograph/dopplergraph, low-resolution helioseismometer, radiometer, particle-and-field experiments.

Programmatic Rationale. The Solar Polar Orbiter is designed to make the first detailed optical observations of the Sun from a high-latitude perspective. As discussed above, this will provide unique, fundamental new data for understanding the structure and physics of the Sun. Similarly, simultaneous observations of the solar surface and solar corona from multiple aspect angles will provide new, unique information about the structure of the solar atmosphere and long-term solar variability. The highest priority spacecraft is the Solar Polar Orbiter (SPO), which should be launched as soon as is feasible. One in-ecliptic GSM spacecraft should be located near the Earth (e.g. at the L1 position). The L1 Solar Monitor (L1SM) spacecraft in the consensus scenario is the forerunner for the GSM series of spacecraft. The second in-ecliptic GSM spacecraft should be located in an orbit approximately 1 AU around the Sun 90 degrees ahead of the Earth (over the west limb of the Sun as viewed from the Earth). The third and fourth in-ecliptic spacecraft should be located in 1-AU orbits on the far side of the Sun and at 90 degrees behind the Earth's orbit (over the east limb of the Sun). If only two in-ecliptic spacecraft are available, one should be in near-Earth orbit, the other could be in a shorter or longer orbit which would permit viewing the Sun from various angles as the two in-ecliptic spacecraft move apart in their orbits. The Solar Probe Companion could serve as an in-ecliptic companion to the SPO and/or other Sun-orbiting spacecraft. The Solar Polar Orbiter would use a gravity assist by Jupiter and or other planets (e.g., the Earth) to reach higher solar latitudes. Earth assist requires a longer time to reach high latitudes than Jupiter assist. However, Earth assist requires a less demanding launch capability.

7.2.2 Proposed New Moderate Solar Physics Missions

7.2.2.1 Orbiting Solar Laboratory (OSL)

Overview. High spatial resolution, coupled with appropriate spectroscopic diagnostics required to measure basic plasma parameters (temperatures, densities, velocities, magnetic fields, chemical abundances), is required to probe the structure of the solar atmosphere and acquire the basic data needed to provide empirical constraints and insights concerning the fundamental physical processes responsible for plasma heating and the transport of mass and energy at, and between, different levels of the solar atmosphere. OSL is listed as "the highest priority mission for initiation as early as 1992" in the OSSA *Strategic Plan* for 1990.

Thematic Rationale. The OSL addresses all three themes given earlier: identification of the variable nature of the Sun, investigation of the short-term variations associated with the evolution of the magnetic activity cycle, and investigation of the magnitude and significance of long-period solar variability and its influence on the heliosphere.

Scientific and Programmatic Rationale. The scientific goals of the OSL are central to advancing our understanding of the basic magnetohydrodynamical and radiative processes that occur in all cool stars (of which our Sun is the premier example). For example, flares, mass loss, and changes in the luminosity of the Sun may derive from the structure and motion of the individual magnetic fibrils at its surface. The individual fibrils can be studied only with an instrument as powerful as OSL. Therefore, progress in developing a scientific understanding of these effects will be seriously limited until OSL is put into operation. Knowledge of solar processes is required in order to develop a scientific understanding of the Sun's control of the space environment of the Earth and of any manned space vehicle in the interplanetary environment. Observed luminosity variations of the Sun, of other solar-type stars, and of the terrestrial climate suggest that the cause of solar luminosity changes are of vital interest to the human race. Achievement of the OSL will significantly enhance the base of expertise in solar physics in the US, and it also will have a far-reaching, positive effect on the training of solar physicists to carry out NASA's research mission in the next century.

7.2.2.2 High Energy Solar Physics (HESP)

Overview. It is essential to acquire high-resolution imaging and spectroscopy of high-energy radiations during the solar maximum. The impulsive phase of a solar flare, for example, can energize both protons and electrons to relativistic energies in a short time, in flare kernels whose size has never been resolved. Sub-arc-second imaging and high-resolution gamma-ray spectroscopy ($R > 1000$) are needed, along with simultaneous photospheric and coronal imaging to provide the context of the flare.

Thematic Rationale. HESP is a solar high-energy astrophysics/flare-physics mission which addresses primarily the second major themes given above, investigation of the short term variations associated with the evolution of the magnetic activity cycle.

Scientific Rationale. Solar high-energy neutral radiations (hard X rays, gamma rays, and neutrons) contain direct information about the acceleration of non-thermal particles in flares and other forms of solar magnetic activity. The impulsive phase of a solar flare, for example, can energize both protons and electrons to relativistic energies, in some cases within tens of seconds. The accelerated particles contain an appreciable or even major fraction of the total flare energy. Observations of bremsstrahlung from the electrons, and of nuclear radiations of

1. ***Spectral Imager for Hard Radiations***

High-energy Detector	Germanium
Energy range	10 keV–10 MeV
Energy resolution	< 1 keV
Angular resolution	< 0.5 arc second
Field of view	Whole Sun
Time resolution	1 sec

2. ***Anticoincidence Shield Response***

Radiation type	Gamma rays, neutrons
Energy range	10–100 MeV
Time resolution	1 msec

3. ***EUV/XUV Spectrograph/Imager***

Aperture	30 cm
Angular resolution	<0.5 arc second
Spectral resolution	TBD

4. ***White-light Telescope (magnetograph/ dopplergraph/H-alpha)***

Aperture	30 cm
Angular resolution	<1 arc second
Field of view	Whole Sun

Table 7-1 HESP strawman payload

several types from the high-energy ions, can reveal the propagation of these particles in the solar atmosphere, showing us the actual site of their acceleration. With HESP observations, we will:

- Identify particle acceleration mechanisms in solar flares and coronal disturbances.

- Study the flow of the energy represented in the high-energy particles.

- Study the plasma physics of non-thermal particle propagation, trapping, and release from the Sun.

- Study abundances and abundance variations in the solar plasma as revealed by nuclear line intensities.

Table 7-1 describes a strawman instrument complement.

Programmatic Rationale. The technology now exists for high-resolution imaging (< arc second) and spectroscopy (R > 1000 in the nuclear line region) of these radiations, even including the neutrons. The High-Energy Solar Physics (HESP) mission proposed here will exploit this technology in an Explorer-class mission (i.e., small to moderate in scope). Related imaging technology has been implemented at low energies and relatively low resolution on the Solar Maximum Mission and Hinotori satellites, and will be flown at 7 arc seconds resolution (FWHM) on the Solar-A (to be launched in 1991). The HESP mission will give us a first opportunity to combine such imaging technology with sensitive high-energy gamma-ray spectroscopy. The maximum science return from such observations requires a suite of simultaneous measurements at wavelengths capable of defining the photospheric and chromospheric dynamics of the flare environment. Vector magnetic-field measurement is one of the essential elements in this suite.

The current mission scenario assumes that HESP will be launched prior to the maximum of solar cycle 24, which is expected to begin at about the year 2011. The mission lifetime of HESP should cover at least three years, with an extension over the entire solar maximum and into the succeeding minimum as a strong desire. The optimum time to fly a high-energy solar mission is during the earlier solar maximum (solar cycle 23) which is expected to occur during the years 2001–2003. This will require an intermediate-class version of HESP with a reduced instrument package made possible by complementary, simultaneous solar observations from OSL. The Pinhole/Occulter Facility proposed as an attached payload for the Space Station Freedom may, if feasible, provide a means of acquiring some high-energy solar observations during solar cycle 23. Solar high-energy observations acquired during the maximum of cycle 23 would complement those of ACE, especially in terms of abundance variability.

7.2.2.3 Mercury Orbiter (MeO)

Overview. In conjunction with energetic-particle detectors, small solar instruments on the Mercury Orbiter, such as a solar neutron monitor, could provide valuable data on solar flares. Simple line-scan imagers can take advantage of the opportunity to use the planet Mercury as an occulter and to use the Mercury orbit for observing the backside of the Sun.

Thematic Rationale. The Mercury Orbiter addresses, to a limited extent, all three themes given earlier: identification of the variable nature of the Sun, investigation of short-term variations associated with the evolution of the magnetic activity cycle, and investigation of the magnitude and significance of long-period solar variability and its influence on the heliosphere.

Scientific and Programmatic Rationale. In conjunction with energetic particle detectors, small solar instruments on the Mercury Orbiter, such as a solar neutron monitor, could provide valuable data on solar flares. Simple line-scan imagers can take advantage of the opportunity to use the planet Mercury as an occulter and to use the Mercury orbit for observing the backside of the Sun.

7.2.3 Proposed New Intermediate Solar Physics Missions

7.2.3.1 Solar Probe Companion

Overview. The Solar Probe will acquire unique, detailed measurements of particles and fields along its flight path, which is expected to come as close as four solar radii of the Sun. These highly unique, critical data need to be analyzed in the context of the larger-scale, time-varying structure of the solar atmosphere. Remote-sensing imaging and spectroscopic measurements made from Earth orbit while the Solar Probe flies close to the Sun are required for observing the large-scale solar atmospheric structure and provision of critical data on the lower-atmospheric sources of the outflowing plasma sampled ***in situ*** by instruments on the Probe.

Thematic Rationale. The Solar Probe Companion studies the coronal source region of the solar wind in conjunction with the Solar Probe and addresses all three major themes given above: identification of the variable nature of the Sun, investigation of short-term variations associated with the evolution of the magnetic activity cycle, and investigation of the magnitude and significance of the long-period solar variability.

Scientific Rationale. A combination of remote-sensing optical measurements and ***in-situ*** measurements of the solar-wind acceleration region can provide unique information on physical conditions in this important region of the solar atmosphere/heliosphere. Remote-sensing imaging and spectroscopic measurements made from the Earth-orbiting Solar Probe Companion while the Solar Probe flies close to the Sun are required for provision of critical data on the lower atmospheric sources of the outflowing plasma sampled ***in situ*** by instruments on the Probe. The physical conditions and processes in the lower atmosphere determine the structure and conditions to be found in the higher layers. The bulk of the plasma heating appears to occur within several solar radii of the Sun. In addition, the plasma changes from a collision-dominated plasma to a collisionless one; the ionization states "freeze in;" the coronal structure changes from being predominantly closed (magnetically) to open; and the solar wind is believed to be accelerated to near supersonic speeds within a few solar radii of the Sun. ***In-situ*** particles-and-fields measurements made close to the Sun can provide critical "ground truth" information for interpretation of remote-sensing data acquired in the same region. This is important because the latter types of data can be acquired over much longer periods of time and in a much larger number of structures than ***in-situ*** measurements made during brief near-Sun "fly-bys" of the Solar Probe. Finally, remote-sensing observations can observe coronal mass ejections from their low coronal origins out to large distances from the Sun.

UV/EUV/white light coronagraphic instrumentation is required to image the white-light corona from the solar surface out to several tens of solar radii and to acquire detailed spectroscopic measurements of coronal densities, temperatures, velocities, chemical abundances, and ion states out to 5 to 10 solar radii (distances beyond the closest approach of the Probe). A low-coronal imaging instrument is required to image the low-coronal structure on the disk (EUV/XUV and/or soft X-ray instrument). Particles-and-fields instruments can provide complementary (to those measured by the Solar Probe) measurements of the solar wind.

Baseline Instruments for the Solar Probe Companion. These include a white-light imaging coronagraph with field of view 1–30 R_{Sun}; an UV/EUV coronagraph/spectrometer with field of view 1–20 R_{Sun}; Soft X-ray imager with a full-Sun field of view; and, if feasible (L1 orbit), several particles-and-fields instruments.

Programmatic Rationale. The Solar Probe Companion must be operational before the Solar Probe reaches ~ 1 AU from the Sun on its inbound leg to observe the coronal origin of the solar wind throughout the time during which the Solar Probe is within 1 AU of Sun. The required instruments are derivatives of instruments under development for the SOHO mission. A Sun-synchronous orbit or L1 location is preferred to enable continuous solar observing during near-Sun passage of the Solar Probe. If the L1 position is available, then it is highly desirable to include particles-and-fields instruments on the companion spacecraft. The Solar Probe Companion can also serve as an in-ecliptic complement to the Solar Polar Orbiter.

7.2.4 Proposed New Small Solar Physics Missions

Small missions which are possible candidates for the Explorer and Small Explorer programs include: Solar Variability Explorer, Solar Composition Explorer, Solar IR Explorer, Coronal Imager, Solar EUV/XUV Explorer, Solar Luminosity Explorer, Flare Radiation Budget Explorer, Tomographic Hectometric Explorer, Flare Build-Up Explorer, Soft X-ray Spectroscopic Explorer, Hard Radiation Anisotropy Mission, Heliospheric Tomography Mission, Ultra-High Resolution EUV Explorer, Neutral Atomic Imager, Gamma-Ray Spectroscopy Mission.

Small satellites provide an ideal means of supplementing instruments on larger spacecraft (e.g., OSL, EOS, GSM) to fill in gaps (in time and/or type of output) in measurements of the output of the Sun. The output of the Sun, viewed as a star, must be measured continuously so that the effects of its variability on the Earth and on space plasmas can be studied and understood. These measurements must include the solar constant and the spectral irradiance for all wavelengths from soft X-ray to the visible. In addition, spectral images for some wavelength bands must be collected over the same time base, so that the solar mechanisms which cause the variability can be determined and eventually predicted. Measurements of the output of low-energy (solar wind) and high-energy solar particles must include data on both the particles and magnetic fields.

7.2.5 Proposed Space Station Freedom Attached Solar Physics Missions

7.2.5.1 Overview

At the time of this writing, the nature and capabilities of the Space Station are evolving. We note that a Space Station can provide a valuable platform for solar observations, as demonstrated during the Skylab mission in the early 1970's.

The Ultra High Resolution Extreme Ultraviolet Spectroheliograph, a set of solar XUV telescopes, had been selected for early deployment on the Space Station. A second-generation attached payload element, the Pinhole/Occulter Facility (with its advanced coronal and high-energy instruments), was also proposed. A capability for small attached payloads would be valuable for innovative instrument development and student involvement.

Early Attached Payload Element. A suite of solar XUV telescopes had been selected for early deployment on the Space Station. This telescope array, known as the Ultra-High-Resolution Extreme Ultraviolet Spectroheliograph, will carry out multi-wavelength observations with innovative technology based upon synthetic multilayer normal-incidence mirrors.

Second-Generation Attached Payload Element. The Pinhole/Occulter Facility will contain state-of-the-art coronal and high-energy instruments, with innovative use of an external occulter at the tip of a 50-m deployable boom. These instruments, if deployed in time for the solar maximum of 1999, can play the role of a solar maximum observatory in place of the HESP free flyer.

Small Attached Payloads. A capability for small attached payloads, on a fixed and simple interface, could serve an analogous role on Space Station Freedom as is presently served on the Space Shuttle by GAS, Hitchhiker, and other "quick" and small payloads. Such a facility would be of extreme attractiveness for innovative instrument development, student involvement, and other uses now reserved for the suborbital programs.

7.2.5.2 Pinhole/Occulter Facility (P/OF)

Thematic Rationale. P/OF is a facility for studying solar high-energy astrophysics, coronal physics, and the physics of solar-wind generation. It addresses all three of the major themes given earlier: identification of the variable nature of the Sun, investigation of short-term variations associated with the evolution of the magnetic activity cycle, and investigation of the magnitude and significance of the long-period solar variability.

Scientific Rationale. The facility uses large-aperture optics for high-resolution imaging and spectroscopy in X rays through gamma rays (pinhole component) and in the UV/EUV/visible coronal radiations (occulter component). The scientific objectives include:

The Impulsive Phase of Flares

- Characterize the conversion of magnetic energy into material heating and motions.

- Determine the mechanism responsible for this energy dissipation.

Solar Activity

- Measure the dynamic events in the "quiet" Sun that cause unexpected brightenings, flows, quiescent prominences, and other manifestations of non-thermal and geometrically complicated structure.

The Corona and Transients

- Study the temporal variability of the classical corona over a wide range of spatial scales (from jets of chromospheric material, heating in magnetic loops, through coronal transients).

- Quantify the generation of high-energy particles in the corona.

- Determine the mechanisms for storage of magnetic energy; energy release, transport, and dissipation; and the driving of mass ejections and acceleration of high-energy particles.

Programmatic Rationale. The Pinhole/Occulter Facility is being studied as a second-generation attached payload for the Space Station Freedom. It could also be flown as a free-flyer. An advanced version could be operated from the lunar surface.

Baseline Instruments. Very high-resolution spectral imager for hard radiations, large aperture white light coronagraph, large aperture UV/EUV coronagraph/spectrometer.

7.2.6 Proposed Space Exploration Initiative (SEI) Associated Solar Physics Missions

7.2.6.1 Enabling SEI Science

Overview. Hard photons and "solar cosmic rays" present a substantial health hazard for astronauts outside the terrestrial magnetosphere. The state of the art in flare physics is inadequate for predicting these health hazards. A concerted effort to improve our knowledge of flares must be made before manned missions are sent into deep space. This requires missions (e.g. OSL, HESP) for conducting the required basic research and deployment of a global network, initially for data-gathering and research, and ultimately as an operational warning system. The lunar surface offers interesting advantages for some types of solar instrumentation such as radio interferometers, gamma-ray observatories, and some types of very high-resolution optical instruments.

Scientific and Programmatic Rationale. Hard photons and "solar cosmic rays" present a substantial health hazard for astronauts. The long voyage to Mars, in particular, would expose astronauts to solar hard radiation as a result of solar flares. Our knowledge of flare occurrence patterns is not deep enough, either empirically or physically, to allow prediction times and intensities with sufficient accuracy to afford much confidence to space travelers. For this reason, a concerted effort leading to much better knowledge of flare occurrence must be made well in advance of manned missions into deep space.

Warning of a solar flare, as far as possible in advance, would be extremely helpful. If such a warning could define windows of safe travel opportunity, that would be even better. We propose a two-pronged approach for this warning: empirical and physical.

Solar activity and flare occurrence are known to be highly organized in time and space, in the sense that occurrence patterns are far from random. The quantitative details of this non-random behavior are not well-known because of the incompleteness and inappropriateness of data, especially as gathered at ground-based observatories. For example, the H-alpha importance of a flare in and of itself can err by many factors of ten as a predictor of the hard radiation associated with the event; indeed, the classical manifestations of a solar flare may not have much to do with the intense, long-lived particle acceleration responsible for most of the risk.

Therefore, the first goal of an observational program dedicated to astronaut safety would be the simple collection of relevant data, as abundantly and extensively as possible, in order to define the nature of the problem statistically. The observations needed would include:

- *Particle fluence measurement.* These measurements should be defined by the need to determine the dose experienced by astronauts; i.e., should have as much fidelity as possible.

- *Flare-occurrence data.* The location and timing of the flare should be determined unambiguously.

- *Flare physical parameters.* The data should define enough of the physical parameters of a flare (e.g., soft X-ray fluence, "superhot" temperatures, gamma-ray line intensity, chromospheric morphology, sunspot configuration, microwave or other radio manifestations, or other features to be decided after appropriate study).

- *Photospheric flows and magnetism.* A relatively simple set of observations, analogous to those of the SOUP experiment on Spacelab-2, could provide information on the distribution of shear (or $v \times B$), of key physical significance.

Armed with data of this type, collected from a network of spacecraft able to view the entire solar surface at all times (at least in the active latitudes), a proper empirical basis for flare occurrence could be constructed for the first time. In view of the major engineering decisions that should await this kind of knowledge, the establishment of even preliminary forms of this network should occur as soon as possible. This initial network should come to a total of three to four spacecraft, at one AU and dispersed in heliolongitude, for full coverage of the solar disk.

At the same time, and on some of the same vehicles, a series of observations devoted to a physical understanding of flare occurrence should take place, again with highest urgency. The linchpin of these observations would be the Orbiting Solar Laboratory, which will provide extraordinary improvements in our knowledge of physical conditions in the photospheric and chromospheric regions of solar flares, including especially the active regions and their environments during the periods preceding the eruption of magnetic fields. Such a simple observation as the horizontal flow patterns of the photosphere ($v \times B$) may well provide the physical key to flare energy build-up, and thus to imminent flare danger.

The high-energy radiations from solar flares are likely to be directly related to the particles emitted into interplanetary space, based upon existing information about particle spectra and event morphology. Thus we should undertake these observations as rapidly and effectively as possible. A new and advanced "solar maximum mission," HESP or the Pinhole/Occulter Facility, should be deployed well in advance of the next solar maximum, ideally by 1998 at the latest. One of the key objectives of such observations will be to clarify and extend the remarkable 155-day periodicity in the most energetic solar flares, noted first during the maximum of 1980. Such observations can help to clarify flare occurrence patterns as well as to define physical conditions of the most relevant types.

OSL & HESP. The OSL will provide critical data for improving knowledge of magnetic-energy storage and release, knowledge which is critical to improving understanding of the physics of flares and their prediction. HESP, whose goal is the study of high-energy phenomena on the Sun, will greatly expand knowledge of the physics of the sources of the hard photons and solar cosmic rays which pose the health risk to astronauts. The Global Solar Mission will provide vital data on the long-term evolution of active regions and the global solar magnetic field. There is increasing evidence that coronal transients and many solar flares are caused by changes in the global coronal magnetic field. Hence, an improved understanding of the structure and evolution of the global coronal magnetic field should lead to improvements in the prediction of flares. Monitoring the back side (as seen from the Earth) of the Sun is critical to improving predictions of flares and other solar activity, particularly for spacecraft at large distances from the Earth, for example, spacecraft bound for Mars. The GSM spacecraft, or their derivatives, will be needed for an operational warning system. For example, a spacecraft located over the east limb of the Sun (as viewed from the Earth) could provide warning of large active regions rotating onto the Earthward hemisphere.

A Warning System. The interplanetary network of solar and heliospheric observatories, described above, should evolve into a warning system to be used operationally during astronaut excursions. Especially during voyages to Mars or other distant locations, the warning system must be capable of direct communication with the astronauts (i.e., of bypassing the long time delays required for links to and from the Earth). We would hope that in one decade's time, the flare warning system could be virtually autonomous, based upon the data gathered in the intervening years and upon modern information-science techniques (artificial intelligence, neutral networks, expert systems, etc.).

Solar science obviously will benefit tremendously from the data gathered in this program, even though its motivation is a practical one, not directly based on research objectives. The OSL and HESP programs, of course, are planned research-quality tools, and indeed the operational and research objectives coincide in the need to develop precise knowledge of flare prediction. Such knowledge would be most soundly based upon comprehensive knowledge of the physics of flares, their necessary conditions, and the causes of their eruption.

The infrastructure developed during human transportation to the planets can be of great use for still-more-advanced solar observations. In noting this, we recognize that the information gained over the next decade will not suffice completely to solve the flare problem, and will instead provide partial solutions and stimulating new questions.

7.2.6.2 Enabled SEI Science

Thematic Rationale. Solar facilities on the lunar surface address all three themes given earlier: identification of the variable nature of the Sun, investigation of short-term variations associated with the evolution of the magnetic activity cycle, and investigation of the magnitude and significance of long-period solar variability and its influence on the heliosphere.

Scientific and Programmatic Rationale. Observatories in space have many advantages for sophisticated observation, for example in unrestricted access to the whole spectrum of waves and particles. In addition free space has certain engineering advantages: no gravitational stresses (little limit on experiment volume or geometry), stable thermal environment, uninterrupted sunlight, and minimal or zero interference from human nuisance. At the same time, the transportation nodes developed for interplanetary travel will probably confer the benefits of frequent access and material transportation, and human presence when needed for repair, adjustment, or deployment. As an important byproduct, then, the Space Exploration Initiative may make it possible to obtain solar observations fully as revolutionary as those of the Apollo Telescope Mount in 1973–1974.

Although most advanced solar observations that we can speculate about for the 21st century should probably be done from free space (if not from the Earth's surface) for reasons of economy and efficiency, there are nevertheless several items for which the lunar surface offers some interesting advantages. Some of these, not necessarily in priority order, are discussed briefly in the following paragraphs:

A lunar radio interferometer. The lunar surface offers vast real estate and a stable platform, which could be used for a set of autonomous radio antennae. These would comprise the elements of a large interferometer, perhaps spread over hundreds of kilometers of the lunar surface. Each unit could have a high degree of autonomy, with its own solar energy supply and communications link to a central "phasing node." The phasing node for a large array would ideally be a lunar satellite, or set of satellites, capable of interrogating each element and correlating the data to obtain visibility functions. Such an approach would work best at low frequencies, 10 kHz–10 MHz, and would permit unprecedented angular resolution for every astronomical target, not excluding "the Earth as a star." The Earth's magnetosphere is known to be very bright as a result of auroral particle activity, and remote sensing from the distance of the Moon would be about right for a comprehensive view.

Large gamma-ray observatories. The lunar material itself can serve as a massive absorber for background reduction. Proposals exist for the use of the water supply of a lunar colony as a potable detector, analogous to the present IMB and Kamiokande observatories.

Advanced pinhole/occulter facility. An extension of the pinhole/occulter concept could make it possible to obtain 0.01 arc-second images of hard X rays and gamma rays from solar and celestial sources.

Large optical instruments. The low-gravity, continuous sunlight during lunar day, frequent (biweekly) eclipses of the Sun at lunar dawn and night, can provide unique opportunities for the operation of large optical instruments capable of acquiring very high-resolution solar measurements.

Appendix A: Key Technology Advancements

Some of the missions included in this plan could benefit from technology advances that would increase mission capability or probability of success. In most cases, the challenges are of an engineering nature and do not require fundamentally new technologies. None are "show-stoppers" (i.e., none pose insurmountable problems). Those that have been identified are discussed briefly in the following paragraphs:

A.1 Cosmic and Heliospheric Physics

A.1.1 Solar Probe

The Solar Probe will have to survive a solar heat load at the mission perihelion of four solar radii ($4R_s$) approximately 3,000 times that at 1 Astronomical Unit (AU), and therefore a lightweight, low-sublimation heat shield capable of protecting the spacecraft and instrumentation from this intense heat load will have to be developed and tested. Material sublimating from the heat shield can become ionized and remain in the vicinity of the spacecraft, affecting the measurement of ***in-situ*** conditions. To avoid this possibility the rate at which mass is lost from the thermal shield must be less than 2.5 mg/s at perihelion.

The swingby of Jupiter prior to the solar encounter will result in exposure of the spacecraft to substantial high-energy radiation. In addition, the solar particle flux at $4R_s$ will also be on the order of 3,000 times that at 1 AU, and a minor solar flare could produce radiation doses capable of adversely affecting spacecraft operation. Significant amounts of nuclear radiation shielding will thus be needed for this mission.

The plasma wave antenna will view the Sun directly without shielding and must be able to withstand the heat load of perihelion passage. While available high-temperature materials should provide acceptable performance, a hybrid concept that combines the conductive properties of metals with high heat resistance would be desirable. Sun sensors will also be required to withstand the perihelion heat load, and some advanced development effort is planned. Because this is a long mission (> 9 years), development of long-life, radiation-resistant, stable instrumentation will also contribute to mission success.

Turbulent plasma near the Sun will produce scintillation effects on the communications link, and a new Ka-Band (32 GKz) downlink system, currently under development to support the CRAF-Cassini program, will be employed.

A.1.2 Interstellar Probe

This is a very long-duration mission (> 25 years), and a systematic longevity evaluation of components, design strategies, calibration procedures, and needed new development will be an important precursor activity. During the mission, the distance between the probe and Earth will reach 200 AU or more, and existing long range communications techniques will have to be improved if high data rates are required.

Instruments to measure the density, velocity, and composition of interstellar neutral gas will require development.

The current Interstellar Probe concept envisions a close solar passage (perihelion at $4R_s$) of the sun with a propulsion stage imparting to the spacecraft a velocity increment (ΔV) of approximately 4 to 5 km/s at perihelion to achieve the required solar system escape velocity. Thus the Interstellar Probe will be subjected to the same intense solar radiation as the Solar Probe mission and require the same technologies. Large liquid propulsion systems capable of withstanding the extreme environments of the mission and achieving the required ΔV will also be a challenge.

A.2 Ionospheric, Thermospheric, and Mesospheric Physics

A.2.1 ITM Coupler

This mission requires the synchronization and control of five or six spacecraft, but appears to be within the present state of the art. However, the highly elliptical orbit of the polar spacecraft poses some aerodynamic and aerothermodynamic concerns for the life of the instrumentation and quality of the data. Some development analysis is needed to understand the magnitude of this potential problem. Very wide-field ultraviolet optics will also be required, and may be a technology driver.

A.3 Magnetospheric Physics

A.3.1 Grand Tour Cluster

A specific consideration of this mission is the inter-satellite tracking system, which must measure the separation between all five spacecraft to within 1% (or 100 m) and orientation relative to inertial space to within 0.01°.

A.3.2 Mercury Dual Orbiter

The hostile thermal environment in the vicinity of Mercury will be one of the key factors for spacecraft design. During the four to six year mission, distance from the Sun decreases to 0.307 AU at Mercury perihelion, with the solar irradiance increasing to just over 10 times that at Earth. Likewise, proximity to the Sun for long durations will require that spacecraft design consider high-energy radiation effects on the spacecraft elements; i.e., surface materials, solar arrays, and onboard electronic systems.

A.4 Solar Physics

A.4.1 High Energy Solar Physics

The gamma-ray spectrometer to be flown on this mission would employ 30 large high-purity germanium detectors (HPGeD) which would have to be cooled and maintained at less than 80° K for optimum operation. Closed-cycle cooling, or a combination of stored cryogen/mechanical refrigerators, may be needed to provide for this requirement for the desired mission lifetime of three years.

A.4.2 Global Solar Mission

A new propulsion system and/or mission sequence would be required to achieve a true polar orbit (inclined 90° to the ecliptic plane) at 1 AU for the polar component of this mission. Although a 90° orbit is desirable, many of the scientific objectives would be met by an orbit with an inclination of about 55°, achievable with current propulsion technology and Jupiter gravity assist.

A.4.3 Solar Probe Coronal Companion (Context)

With a lifetime of over 2.5 years required to accommodate two successive solar passages by the Solar Probe, effects of the space environment upon the multilayer-coated telescopes of the soft X-ray imager may require special consideration.

Appendix B: Panelists

Panelists, Strategy-Implementation Study

Magnetospheric Physics Panel
J. L.Burch (Chair)
M. Ashour-Abdalla
D. N. Baker
C. A. Cattell
A. F. Cheng
C. K. Goertz
M. G. Kivelson
L. Lee
T. E. Moore
T. A. Potemra (Co-chair)
P. H. Reiff
E. G. Shelley
J. A. Slavin

Solar Panel
G. L. Withbroe (Chair)
S. Antiochos
G. Brückner
R. R. Fisher (Co-chair)
J. T. Hoeksema
R. P. Lin
R. Moore (R)
R. R. Radick
G. Rottman
P. Scherrer
D. Spicer
K. T. Strong
H. Zirin

MI&DS Panel
C. F. Kennel (Chair)
T. M. Donahue
R. W. Farquhar
J. L. Green
A. Hasegawa
S. M. Krimigis (Co-chair)
W. S. Kurth
D. Muller
E. J. Smith
D. F. Strobel
D. Cauffman
R. Zwickl

Ionospheric/Thermospheric/ Mesospheric Physics Panel
E. P. Szuszczewicz (Chair)
L. H. Brace
A. B. Christensen
B. Fejer
R. A. Heelis
M. J. Keskinen
T. L. Killeen (Co-chair)
N. C. Maynard
H. G. Mayr
C. I. Meng
R. G. Roble
R. W. Schunk

Cosmic & Heliospheric Physics Physics Panel
R. A. Mewaldt (Chair)
A. Barnes
W. R. Binns
L. F. Burlaga
M. L. Cherry
T. E. Holzer
J. R. Jokipii
W. V. Jones
J. C. Ling
G. M. Mason (Co-chair)
P. Meyer
M. Neugebauer
M. E. Wiedenbeck

Theory Panel
M. Ashour-Abdalla (Chair)
S. Antiochos
S. Curtis
B. Fejer
C. K. Goertz
M. L. Goldstein
T. E. Holzer
J. R. Jokipii
L. Lee
H. G. Mayr
G. L. Siscoe
D. Spicer
D. F. Strobel
R. Walker